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A conceptual framework for an urban areas typology to integrate climate change mitigation and adaptation ☆

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ABSTRACT

Urban areas are key sources of greenhouse gas (GHG) emissions and also are vulnerable to climate change. The recent IPCC Fifth Assessment Report illustrates a clear need for more research on urban strategies for climate change adaptation and mitigation. However, missing from the current literature on climate change and urban areas is a conceptual framework that integrates mitigation and adaptation perspectives and strategies. Because cities vary with respect to development histories, economic structure, urban form, institutional and financial capacities among other factors, it is critical to develop a framework that permits cross-city comparisons beyond simple single measures like population size.

The primary purpose of this paper is to propose a conceptual framework for a multi-dimensional urbanization climate change typology that considers the underlying and proximate causes of GHG emissions and climate change vulnerabilities. The paper reviews some of the basic steps required to build such a typology and associated challenges that must be overcome via a demonstration of a pilot typology with nine case study cities. The paper shows how the proposed framework can be used to evaluate and compare the conditions of GHG emissions and climate change vulnerability across cities at different phases in the urbanization process.

☆ All authors were equally responsible for the development of the paper. The paper emerged as a result of group workshop discussion. Karen Seto and William Solecki took the leadership role of developing the paper in its final form.

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1. Introduction

The recent Fifth Assessment Report of the IPCC presents a clear indication of the how the conditions of climate adaptation and mitigation still operate largely in separate worlds – both intellectually and operationally. The objective of this paper is to actively focus on the opportunities for promoting more connection between climate change adaptation and mitigation in urban areas, and with specific focus on the definition and articulation of a typology tool designed to investigate climate vulnerability and greenhouse gas emissions (GHG) contexts of individual cities or sets of cities.

It is becoming increasingly obvious that there is a need to reconcile the vulnerability-adaptation and emissions mitigation dimensions of climate change with respect to cities.[1] The recent IPCC reports (WG 1, 2, 3 and Synthesis Report) all focus on the demand for accelerated action.[2] However, these reports pay little attention to human settlements, whether they are towns, cities or large urban agglomerations (with Chapter 8, WG 2; and Chapter 12, WG.3 notable exceptions) It is thus important to ensure that climate adaptation and mitigation *in cities* occurs at the same time, and most often in ways that are collaborative and synergistic (i.e. leading to co-benefits and not situations for example where adaptation strategies that could heighten GHG emissions).

Cities have been recognized as important sites of global climate action. Cities have become global leaders in addressing climate change through greenhouse gas mitigation and an increasing focus on the need for climate adaptation (Rosenzweig et al., 2010). The September 2014 Mayors Declaration at the UN Summit which highlight the goals of more rapid moment on climate adaptation and mitigation (http://www.un.org/climatechange/summit) is further evidence of this commitment. The IPCC AR5 report and similar assessments (e.g. US National Climate Assessment) illustrate the spectrum of conditions across the universe of cities with respect to adaptation and mitigation strategies, actions, and capacity. For instance, Chapter 12 of AR5 introduces the classification of cities as "net producers, trade-balanced, and net consumers." It also identifies four key urban factors potentially leading to urban GHG reductions: "density, land-use, connectivity, and accessibility." Furthermore, it looks at mitigation options and scenarios appropriate for small vs. large cities.

The wide diversity of cities speaks to the need for understanding the contexts under which these variations have emerged and the situations under which there has been more forward movement to effective adaptation and mitigation than in others, and under what circumstances has meaningful forward movement been made on both activities simultaneously. It is these examples that will be most important for other cities to study and potentially emulate. Urban areas are important sources of GHG emissions and are also vulnerable to climate change. A rapidly growing literature exists on city-specific climate change strategies with a majority of these efforts describing the actions taken by individual cities. Missing from the current understanding is a framework that connects how metrics of cities and the broader scale process of urbanization (defined here as the sum of the conditions which result in the [re]building of cities – see Solecki et al., 2012) connect with metrics of climate change.

The primary objective of this paper is to propose and describe a conceptual framework for an urbanization-climate change typology that simultaneously considers the drivers of urban GHG emissions and vulnerabilities to climate change. The elements and variables defined in the framework reference the key assertion and finding generated by the AR5 WG2 and WG3 reports generally, and the urban-focused chapters in the two reports specifically. Building off these recent efforts, the framework is structured to be useful for the identification of effective points of cross-urban comparisons and potential intervention in these urban systems across a diversity of settlements, urbanization processes and geographies.

A framework of this type also can be used to facilitate the testing of potential climate change mitigation and adaptation strategies within and across groups of cities by allowing investigators to define levels of association within and between these two categories of variables. The research literature makes it clear that cities are beginning to engage with the threat of climate change, and their condition and capacity to act varies widely. Understanding what metrics cities can use to facilitate climate change action comparisons, and what these comparisons might signify is part of the overall rationale of this work. In this regard, the typology enables the organization and comparison of the large and growing number of case studies on urban strategies of climate change mitigation and adaptation. Overall, the construction of the typology is designed to address two fundamental and interrelated questions about cities. They are: A. What conditions are consistent with having both a significant amount of adaptation and mitigation planning and practice?; and, B. What conditions are consistent with promoting both high levels of adaptation and mitigation moving into the future?

The paper is organized into the following sections. First we discuss the case for an operational and analytical connection between climate vulnerability and GHG emissions. Next we define a theoretical understanding of how these elements can be connected, and how conditions for enhanced adaptation and mitigation can be made possible. In the following section we propose a process to develop the typology that provides understanding of the connections and serves as hypotheses testing

[1] We distinguish between the terms vulnerability and resilience. While resilience theory has informed vulnerability analysis, resilience in of itself represents a different process associated with the 'ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions' (IPCC SREX, p. 563).Vulnerability can be defined as the propensity or predisposition to be adversely affected (IPCC SREX 2011) and as the "susceptibility to damage or harm" which results from conditions of exposure and adaptive capacity (Eakin and Luers, 2006; Adger, 2006; Field et al., 2012). Adaptive capacity of individuals or households can be defined by the conditions of available resources (e.g. insurance, wealth), networks (e.g. social capital, supportive family and friends), information access (e.g. knowledge of emergency services), physical health, and other site- and situation-specific characteristics. At an aggregate level, adaptive capacity depends on the resilience or robustness of social and ecological systems (Polsky et al., 2007).

[2] Many of the authors of this effort were contributors to the AR5 volumes, specifically WG2 Chapter 8 and WG3 Chapter 12.

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and policy testing device. The final sections include an application of the typology to set of cities and discussion of the implication of applications.

2. Conceptual and operational connections between GHG emissions and climate vulnerability

Cities are at the center of the climate change challenge. Urban areas are key development and climate players contributing more than 90% to global gross value (Seto et al., 2012) and consuming between 56% and 76% of global energy produced (Marcotullio et al., 2013; IPCC, 2014). The impact of urbanization on climate is likely to increase given future urban population and economic growth trends. With more than half of the world's population living in urban areas and an increased percentage in the future, urban areas make up the greatest concentration of climate vulnerable people and infrastructure. Yet, despite the global importance of urbanization and urban areas, the science and policy communities have few empirical measures to examine and compare them in the context of climate change. Currently, urban population size is the only metric that is available for nearly every city in the world, and, therefore, it is the most common metric to categorize and compare cities and urban areas.[3]

A nascent literature has begun to form that examines the planning, management and operational connections between climate adaptation and mitigation (Pizarro, 2009; Kress, 2007; Duguma et al., 2014; Walsh et al., 2013; Wise et al., 2014; Juhola et al., 2013). The planning research community has paid special attention to the "conundrum" (Pizarro, 2009) where opportunities to advance mitigation might have negative implications for adaptation and vice versa (see also Biesbroek et al., 2009; Hamin and Gurran, 2009; Laukkonen et al., 2009; Roy, 2009). The identification of adaptation and mitigation action co-benefits and "win–win" solutions is a central goal of these investigations. At the same time, it is recognized that these efforts need to simultaneously enhance social and environmental equity and economic development. Concurrent with these conditions is that adaptation and mitigation action also will require more robust spatial planning, flexible urbanization, and resilience against extreme stresses and shocks in a non-stationary policy context (Solecki and Rosenzweig, 2014).

Effective adaptation and mitigation planning demands clear metrics of success (e.g. to monetize benefits of these actions to promote financing), a protocol to identify and construct policy levers, and tools for enhancing social and ecological capacities. Conceptualizing urban areas as sets of intersecting systems provides the basis to study the structure and organization of urban systems and their operational capacity including the speed, volume, and direction of resource flow and response to change and stress. These conditions illustrate the need and requirements for an urbanization and climate change typology. A typology of this type should include a range of urban system relevant variables such as equity, economic activity, resilience, and governance capacity.

It is important to note that the conceptual framework presented here can be seen as a broad roadmap, and not as a detailed or fully operational toolkit. The typology is discussed within the context of a descriptive narrative with illustrative examples of how it can be constructed and implemented. The goal is to present and assess the conceptual elements, organization and areas of potential application of such a typology and the connection and integration between the underlying concepts of greenhouse gas emissions reduction and mitigation, vulnerability and adaptation. The potential uses of a fully specified and operational typology include helping urban decision-makers prioritize on actions for adaptation and/or mitigation, in addition to track potential progress and comparing cities to one another and could connect with the on-going shared socio-economic pathways work (see O'Neill et al., 2014) and related efforts attempting to define links between vulnerability and adaptation and emissions and mitigation (see Future Earth, Urban Climate Change Research Network).

The typology is constructed within the realm of what is practical and around the use of a parsimonious set of variables that are most widely accessible for the largest set of cities. A critical constraint for applying the framework is the limited amount of comparable data sets across a wide array of cities (i.e. big, medium, and small cities in developing and developed country contexts). An ambition of this effort is to create a framework that can be used to examine, connect, and compare cities with the data that are widely available now, but could be expanded as additional data for a larger set of variables and a greater number of cities become available. In sum, we present a simple exercise to illustrate the character of existing city data that could be incorporated into a typology and the constraints associated with the data.

3. Typology framework

Urban researchers often have tried to categorize and organize cities with typology frameworks.[4] Typologies are descriptive and analytic tools that help to develop and refine concepts, tease out underlying concepts, create categories for classification and measurement and sort case studies (Collier et al., 2012). Recent examples of urban or city focused typologies have been

[3] Change in urban population size also is the most often used metric of the process of urbanization. However, even population size is not consistently measured across cities because of different boundary definitions. For example, New York City as of 2010 had a population of approximately 8.3 million residents (US Census, 2011) when counting the population that lives within the city's municipal boundary, but the entire New York Metropolitan Region has a population of about 22 million. Similarly, the definition of what constitutes an urban area varies considerably from country to country.

[4] As early as 1921, famed sociologist Max Weber introduced a typology of cities that included perspectives from economics, politics, and institutions (Weber, 1958). Since then, cities, urbanization, and starting in the late 1980s climate change have been studied in many contexts where typologies have played a role.

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developed to provide historical narratives, categorize urbanization and development trends, examine a range of issues including environmental impacts, and classify cities by population size or economic activity (see Table 1). These data exercises and typology must wrestle with variety of conceptual and methodological issues that underpin ongoing debates within the field of comparative urbanism. Critical issues include the validity and reliability of data comparison for cities set in vastly different social, economic, and political contexts (see Nijman, 2007; Kloosterman and Lambregts, 2007; and Bulkeley et al., 2015)

A typology should use a suite of factors that are justified theoretically from the research literature, available directly or by proxies, and are immediately relevant to the question at hand. Existing urban typologies provide useful insights into the definition, construction, and the use of variables relevant to urbanization and climate change (Creutzig et al., 2015). For example, successful typologies need to be based on variables that are generally available for a wide range of cities and variables for which there are relatively consistent definitions. Existing typologies also provide examples of how to illustrate change over time of urban variables and of scaling protocols that allow for the integration of several variables into specific dimensions. The inclusion of dynamic properties provides significant added value of a typology because it could be used to assess or calculate the relative impact of policy shifts or other large-scale impacts.

The core of the typology framework presented here is an organizational structure that facilitates integration between the characteristics of a city, ongoing urbanization processes, GHG emissions and climate vulnerability, and policies aimed at climate change mitigation and adaptation.[5] Essentially the typology involves a set of data reduction steps through which a set of values for a range of variables can be consolidated to define vulnerability and emissions metrics that could become data values for a vulnerability-emissions graphing exercise.

The overall structure of the Urbanization-Climate Change Typology Framework development process is illustrated in Fig. 1. The Urban Characteristics Matrix (UCM) includes a range of city-level variables that can be collectively portrayed, for example via a spider diagrams. These variables reflect the current conditions within each city yet could be altered via policy interventions. The UCM can be used to derive indicators associated with emissions (Urban Emissions Indicators – UEI) and indicators associated with vulnerability conditions (Urban Vulnerability Indicators – UVI). Generic emissions indicators (e.g. urban form and accessibility, consumption and living and housing), and generic vulnerability indicators (e.g. hazards, exposure, sensitivity, and adaptive capacity) derived from the AR5 reports and other recent literature are also illustrated in Fig. 1 (and described more Section 3.3). Variable aggregation and data reduction strategies such as rank-ordered and averaging can yield vulnerability and emissions that define X, Y coordinate values, respectively, that can be mapped onto a graph (here defined as the Emission-Vulnerability Plane [EVP]).

For the emission-related indicators of the typology, urban form and accessibility relate to how horizontal and vertical domains of the built environment affect population density and impact on transport emissions. Urban form and accessibility also indicate the spatial pattern of destinations and human activity within cities and their peripheries, which have direct (travel demand) and indirect (need for travel beyond city limits) effects. Urban form and accessibility includes what is typically posed in terms of the six “Ds:” density, diversity, design (Cervero and Kockelman, 1997) destination accessibility, distance to transit (Ewing and Cervero, 2001) and demand management (Ewing and Cervero, 2010).

Living and housing subsumes the energy efficiency of housing and appliances but also the individual floor area for residents and retail stores. Consumption accounts for the embedded emissions of products consumed from both products made locally (i.e. within a city) and from outside the city. Living and housing type includes the influence of lifestyle and culture. For example, cultural norms can influence GHG emissions, including, inter alia, mealtime customs (Bulkeley, 2013) and preferences for housing types (Leichenko and Solecki, 2005).

Consumption includes total consumption that could be further disaggregated into population and affluence. Both population size and affluence (for example, GDP) are significant influences of urban GHG emissions (Kennedy et al., 2009a,b; Marcotullio et al., 2013). While each of these dimensions comprises numerous individual contributions to emissions, a clustering of emissions along these dimensions reveals interesting patterns, particularly for municipal policies. As a notable example of work illustrating this approach, a recent study hybridized global supply chain data with energy-use and life-style data in UK municipalities and disentangled territorial emissions from consumption-based carbon footprints (Minx et al., 2013).

Urban vulnerability in the typology can be measured as a function of four indicators: (1) hazards – probable or looming perturbations and stresses to urban systems; (2) exposure – the extent to which urban populations, economic activities and built environments are in contact with, or subject to hazards; (3) sensitivity – the degree to which some urban populations are more susceptible to hazards with patterns of susceptibility, often based on demographic or physical characteristics; and (4) adaptive capacity – the ability to avoid or lessen the negative consequences of climate change based on access to resources, assets and options to introduce policy changes to expand the range of variability with which urban populations can cope (Romero-Lankao et al., 2012). The vulnerability indicators could be validated using expert knowledge and further tested via internal and external validation techniques to assess the relative magnitude of exposure, sensitivity, and adaptive capacity of a city or clusters of cities.

[5] For the discussion here, cities as defined by municipal boundaries are the primary units of analysis. It is recognized with local (within boundary) and non-local, contextual variables including for example state (provincial) and national economic conditions and policies all will influence the emissions and vulnerability levels of individual cities, and that teasing out the relative contributions of these factors is complex (see Sellers, 2005).

Table 1
Existing urban-related typologies.

Subject	Basis of typology
Transportation	Transportation modes: e.g., walking city, streetcar city, automobile suburbs, edge cities (Barter, 1999; Creutzig et al., 2012; Knox, 2010)
Urban planning	Spatial structure: e.g., compact, dispersed, polycentric (Jabareen, 2006)
History	Historical function: e.g., defense/strategic, mercantile, commercial (Mumford, 1968; Knox, 2010)
Demography	Demographic variables: e.g., fertility, mortality, migration (Montgomery et al., 2003; Balk et al., 2009)
Economic geography & urban economics	Socioeconomic variables and land use: e.g., gross domestic product, population growth, agglomeration economies, distance, trade (Romero-Lankao et al., 2008; Rosenthal and Strange, 2001; Duranton and Puga, 2004; Anas et al., 1998)
Power laws and scaling	Population rank statistics and similar metrics (Bettencourt et al., 2007; Batty, 2008; Fragkias and Seto, 2009)
Urbanization and vulnerability	Urbanization and socio-economic development and selected indicators for exposure, sensitivity and adaptive capacity (Garschagen and Romero-Lankao, 2013)

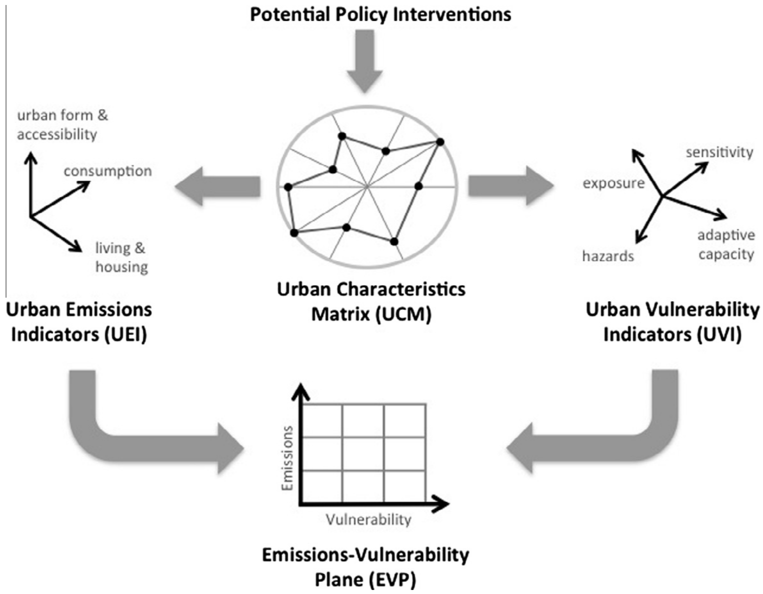

Fig. 1. Schematic of the Urbanization-Climate Change Typology Framework (UTF).

3.1. Urban characteristics matrix diagram – dimensions and development process

A critical part of the typology is structuring the spider diagrams of emissions and vulnerability related variables for each city. The composition and structure of each diagram is reflective of the conditions present in the city and allows for the integration of several different dimensions each of which would be composed by numerous empirical variables. To illustrate the process of how Urban Characteristics Matrices can be constructed for the proposed typology, one could consider a range of variables associated with the emission and vulnerability level of cities. The variables could be grouped into a set of dimensions that are reflective of the current understanding in the climate literature.

Given the diversity of cities, the criteria for choosing the dimensions and variables should be comprehensive enough for any urban area (or urbanization process) to be represented either by currently available data (Howse et al., 2001) or data that can be specified for that purpose via existing data sets (e.g. derivative products, remotely sensed data). Table 2 includes sample emissions and vulnerability variables that can be utilized in the UCM diagram and used to construct the emissions and vulnerability indicators.[6]

Criteria for defining the UCM dimension axes would be based on their capacity to illustrate qualities of GHG emission (and mitigation), and for climate vulnerability (and adaptation) and could involve an iterative process in which different

[6] However, the typology as constructed would not necessarily make reference to the drivers and processes that created the conditions in each city. For example, many of the determinants of emissions and vulnerability are a product of policies by higher-level government agencies and the national context. As a result, cities cannot be seen as separate independent entities. A variety of non-local interventions occurring at the national, regional, NGO, and private sector scales could have a direct urban influence. For urban transportation, as example, interventions could include increased funding for public transit, policies discouraging private automobile use or the promotion on alternative fuel transport. To fully operationalize the typology, an understanding of these possible interventions and definitions of each resulting variable to be included needs to be vetted and standardized.

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Table 2
Urban Characteristics Matrix Variables. Includes sample variable dimensions and specific variables that could be used within the Urban Characteristics Matrix Spider Diagram. The variables within each category are listed in general order of general availability – from frequent to infrequent.

Demographics
Total population
Age structure
Proportion of population who have migrated to city within past 5 years
Socio-economics
Income
Income inequality
Average years of schooling
Schooling inequality by income and gender
Insitutions and governance
Years since incorporation-formal
Number of jurisdictions in metro region
Measure of spatial centrality
Ecosystems and resources
Water availability (scarcity)
Temperature and precipitation
Arable land
Built environment, location and land use
Total built land area
Urban perimeter
Fraction pop. living in informal settlements
Flooding vulnerability
Coastal vulnerability
Local pollution
Vertical dimension of city
Infrastructure
Presence of public transit rail system
Transportation infrastructure (e.g. subway or road length)
Transportation modes (quantitative shares)
Energy resource (generation and fuel mix) profile

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dimensions are statistically or descriptively compared. In Fig. 2, an Urban Characteristics Matrix spider diagram[7] is presented for 10 specific axes for two hypothetical cities (City 1 and City 2). The values of five of the axes are similar for the two cities while for five others (socio-economics clockwise to natural resources) the values differ.

3.2. Spider diagrams to emissions and vulnerability indicators

The Urban Characterization Matrix spider diagrams provide the structural foundation for the typology framework. The next step in this building process is to translate the UCM spider diagrams into emissions and vulnerability indicators. This process can take place in myriad of different ways and could be constructed to assume a more exploratory-analytical approach (e.g., using statistical applications such as factor analysis to define indicators) or a more normative approach (e.g., thereby using predetermined indicator categories defined within the existing literature). Here, we use a more normative approach given the overall exploratory nature of discussion. In response, the translation process defined here takes place in two steps: first, defining emission and vulnerability dimensions from the spider graphs, and second, defining and reconsolidating variables in each set of dimensions together to identify emission and vulnerability indicators and their values. Fig. 3 illustrates the process with three generic emissions indicators (in blue) and four generic vulnerability indicators (in green). A variety of data reduction techniques could be used to convert the diverse set of empirical emission and vulnerability variables and dimensions highlighted in the UCM to component values of each indicator, and eventually to a single value, each for emissions and for vulnerability.[8]

The final product of the UCM spider diagrams and data reduction-derived indicators are emissions and vulnerability index values for each city that can be placed on the emissions-vulnerability plane (see Fig. 3, Item C). The *Y*-axis is used to locate the index value of emissions and the *X*-axis is used to locate the index value of vulnerability. Depending on their data, a city will be located at a specific *X*, *Y* coordinate location on a graph (e.g. the emissions-vulnerability plane – EVP). Cities located near the *X*, *Y* intercept will have both low emissions and vulnerability scores; while cities with both high *X*, *Y* values will be located most distant from the intercept.

This graphic plane serves an important opportunity to map the interconnections between emissions conditions and vulnerability conditions of specific cities. As the EVP is populated with city points – clusters of cities with similar *X*, *Y* indices values can be distinguished and identified. The trajectory of a specific city at various time periods also can be mapped. The mapping of data for different time periods will allow for the illustration of emissions and vulnerability trajectories and pathways that result from recent or future, scenario-based, interventions or for inaction.

3.3. A sample application of the framework concepts

A sample application of emissions and vulnerability variable index development and graphic mapping illustrate many of the opportunities and challenges of this approach. In this demonstration presented here, data for emissions and vulnerability related variables were collected for a set of nine cities (Accra, Bangalore, Boise [US], Durban [South Africa], Freiburg, Istanbul, Kampala, New York, and Rio de Janeiro) with populations ranging from a few hundred thousand to more than 10 million. Data for 44 widely available variables were collected and classified.[9] To facilitate comparison, variables units and definitions were standardized.[10]

The variables were reviewed and critically assessed based on the research literature and expert knowledge. The variables first were classified with respect to whether they were illustrative of city-level emissions or vulnerability, or could be related to both vulnerability and emission potential.[11] Other categories included those variables related to response capacity of a city (either for emission or vulnerability action), and a group of contextual variables defined in the literature as important for understanding urban function and urbanization. The variables represented variables identified in the five variable dimensions presented in Table 2.

The values for the emissions and vulnerability variables were rank-ordered across the set of nine cities. The ranking for each variable was organized from 1 to 9 (1 ~ lowest emissions potential or lowest vulnerability potential and 9 ~ highest emissions potential or highest vulnerability potential). An average rank value across the emissions and vulnerability variables was calculated for each of the nine cities and used to define *X*, *Y* coordinates on the graph (see Fig. 4). Cities toward

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[7] UCM spider diagrams allow researchers and policy-makers to identify potential drivers or interventions that may contribute to changing the locality's position on the Emissions-Vulnerability Plane. The sensitivity of these positions can be determined for each specific city and compared across a set of cities.

[8] Data reduction techniques typically involve reducing the variables from a higher level of measurement to a lower level of measure (e.g. from interval to ordinal) and then organizing the data via a ranking process through the use of an index or scaling protocol, either with or without a variable weighting assumptions. In the manuscript, we use a very basic mode of data reduction – simple ranking of the observations from greatest association (or value) to lowest association (or value) as defined by the variable in question and then calculating an average ranking across all the variables for each city.

[9] See technical Appendices A and B for presentation of the variables and associated references.

[10] City data were derived from the Solecki and Rosenzweig (2014) and individual manuscript authors and were developed into a common database by Stephen Solecki.

[11] The term potential here is used to illustrate the condition that emissions and vulnerability measures will include both quantitative and qualitative data with varying levels of validity and reliability. The combination of these two types of data in a order rank fashion is an attempt to recognize the precision limits of data and also enhance the validity and reliability of the composite measure. The term 'potential' is not used to connote a future condition (i.e. a projection) but to describe the current state for each city. It also should be recognized that observed emissions data was included in the composite measure of emissions potential for each city.

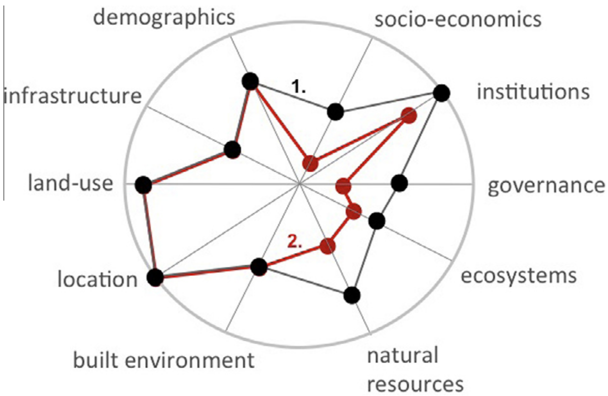

Fig. 2. Urban Characteristics Matrix. Urban characteristics matrix spider diagram of potential variables to illustrate dimensions of emissions and vulnerability conditions for cities City 1 (in black) and City 2 (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the *X*, *Y* axis can be seen as having lower emissions and vulnerability potential while those on the upper right of the graph can be seen as higher emissions and vulnerability potential.

The distribution of the cities on the graph plane has face validity and reflective of the expected relationships among a diverse set of cities such as those presented. For example, the cities with the highest vulnerability potential are low to medium income cities in the global south and often associated with increased exposure and lower hazard response capacity. The results for high emission potential cities are more complex with cities in both the global north and south in the higher rankings. A general grouping of cities with similar income levels seems to be present with higher income cities (Boise, Freiburg, New York), medium income cities (Bangalore, Istanbul, and Rio de Janeiro), and lower income cities (Accra and Kampala) in close proximity. Durban (ranked lowest for emission and vulnerability potential) presents an interesting outlier and warrants further investigation and could be supplying new insights.

This sample application presents intriguing results. Several critical conditions were observed with data reduction applications of this type. Data availability and variable comparability across the sets of cities was a primary concern. The lack of data availability would be especially a problem in small and medium sized cities in the global south where regular data collection and processing might not take place, but where such data are sorely needed because these are the fastest-growing cities. Another key challenge is consistency of the association between the variables and expected contribution to the emissions potential and vulnerability potential. The framework approach makes an *a priori* assumption that the association between the variables, and emission or vulnerability potential are consistent across the set of cities – e.g., that variables like income inequality have similar contribution to vulnerability across the set of cities. Other considerations include the

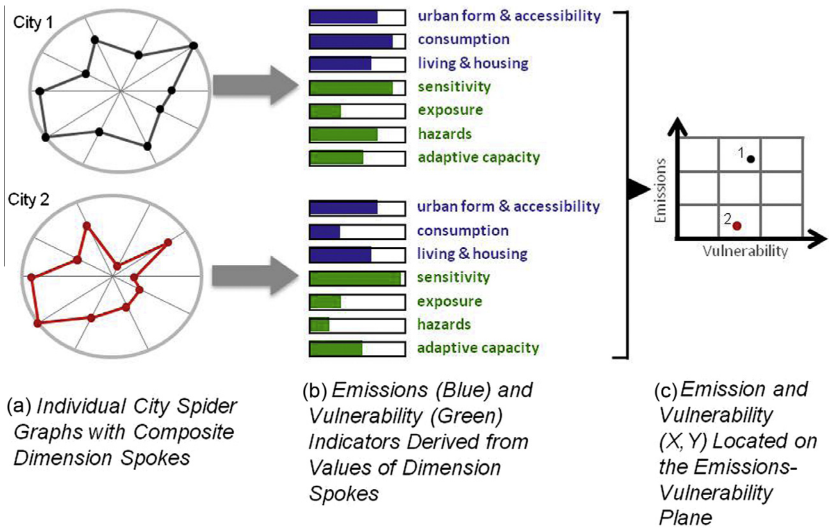

Fig. 3. Potential Emissions and Vulnerability Indicators. Illustration of potential emissions and vulnerability indicators that represent a composite of dimensions defined by individual city UCM spider diagrams and translated to indicator. Two cities (City 1 and City 2) are presented in the figure; the length of the blue or green shading illustrates different city-specific indicator values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

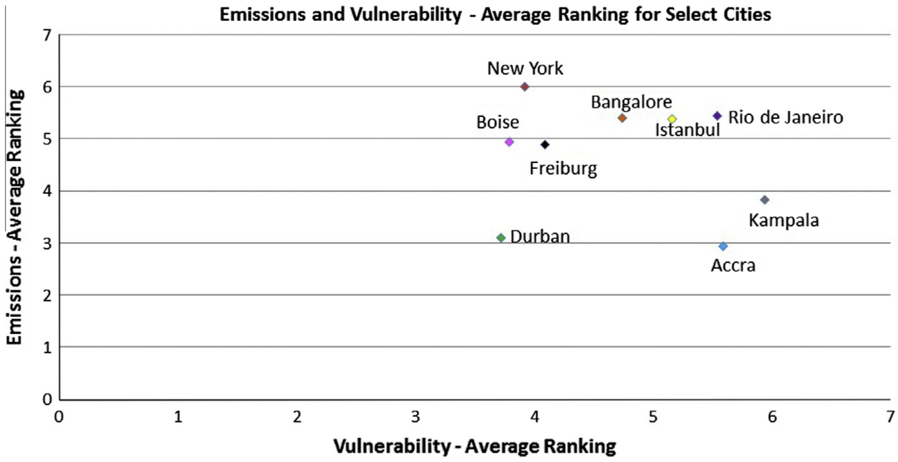

Fig. 4. Emissions and vulnerability average ranking for nine select cities.

potential collinearity within the sets of variables and between the sets of variables (e.g. between emissions variables and vulnerability variables). For example, higher population density can be associated with reduced GHG because of the potential increased effectiveness of public transit infrastructure but can be also associated with increased concentrations of at-risk populations.

3.4. Emission and vulnerability indicators

The sample application revealed that the success of the typology framework will be dependent on access to appropriate, consistent and transferable variables from a set of cities. Recent efforts to create standardized urban sustainability variables via ISO metrics process shows that this process of regimentation of city data for cross comparison is starting to appear (see World Council on City Data ISO 37120). As this discussion moves forwards and as the opportunity for a more robust emissions-vulnerability typology advances, several important considerations regarding data should be noted.

3.4.1. Urban emission indicators

The emission rankings in Fig. 4 attempts cover a number and type of end-use sectors including waste and wastewater, energy supply, transport, commercial and residential buildings, industry, agriculture and forestry (Dodman, 2009; Weisz and Steinberger, 2010; Kennedy et al., 2009a,b). Identifying the GHG emissions from each of these sources requires substantial background data. For example, transportation issues should include mobile CO_2, CH_4 and N_2O emissions, emissions from non-highway vehicles, alternative fuel and electric vehicles and fugitive emissions from motor vehicle air conditioning (ICLEI, 2008). A number of different estimation methods are present for each of these emissions levels.

Greenhouse gas emissions for individual cities more frequently have been estimated rather than observed or measured (Marcotullio et al., 2012). Researchers have developed inventory protocols to help in the estimation process (Ramaswami et al., 2008; Kennedy, 2012; Kennedy et al., 2009a,b). Urban emissions variables, dimensions and indicators in the typology were derived from a review of existing literature and include aspects of how GHGs are estimated in total and per different energy fuel mixes, what category of emissions dominate (i.e. Scope 1, 2, or 3 emissions; see World Resources Institute and World Business Council, 2013), and where the emissions take place as defined in IPPC AR5, WG3, Chapter 12. Chapter 12 of the AR5 WG3 introduced a set of useful classification of cities such as "net producers, trade-balanced, and net consumers". It also identified four key urban factors potentially leading to urban GHG reductions: "density, land-use, connectivity, and accessibility."

Including Scope emission dimensions in the typology could allow a more complete understanding of total emissions and comparison of emissions from different cities. Local inventories also include emissions from activities of businesses and residents located within the study area, most often "direct" Scope 1 emissions. Typologies of direct residential and transport emissions/energy use have recently been developed with high spatial resolution for England (Baiocchi et al., 2015), and globally for 274 cities (Creutzig et al., 2015). Measurements also may include activities located outside the local jurisdiction but closely related to economic activities that are conducted within the jurisdiction, known as "indirect" emissions, described as Scope 2 emissions (Lebel et al., 2007) (e.g. regional, outside the city power production and waste disposal fulfilling energy and waste disposal needs of urban residents and businesses). Emissions from resource extraction and material production (e.g. industry) are described as Scope 3 emissions and could be defined as occurring within a city boundary or outside the city.

3.4.2. Urban vulnerability indicators

In the proposed typology, the vulnerability component focuses on urban vulnerability including factors defining the vulnerability of the urban system (e.g. changes in age structure as it affects sensitivity or in human, social, physical, financial, natural capital elements influencing capacities to adapt) and urbanization processes (e.g. drivers of changes in concentration of people and activities in risk-prone areas, or in densely or otherwise sprawling built environments). These vulnerability indicators can be related to levels of urbanization and socio-economic development and the association between rapid urbanization and economic transformation, and significant adaptation challenges (Garschagen and Romero-Lankao, 2013).

Research on urban vulnerability has grown considerably during recent years, yet is primarily composed of case studies based on conflicting theories and paradigms (Adger et al., 2009; Eakin et al., 2009; Eakin and Luers, 2006; Adger, 2006). These approaches tend to focus on different subsets of dimensions and mirror those on vulnerability in the general environmental change context: natural hazards, political economy (or ecology), and ecological resilience (O'Brien et al., 2007; Romero-Lankao and Qin, 2011; Leichenko, 2011). As an example, in addition to modelling exposure and sensitivity to harm within a "vulnerability as impact" tradition, increasingly more integrated lineages (e.g. "urban resilience") have emphasized the need to assess adaptive capacity, or the ability of people and places to recover from perturbations. In sum, while vulnerability research has advanced considerably in recent years, a clear opportunity and need exists for a standardized set of urban vulnerability variables.

4. Application opportunities and implications

The typology framework presented here can provide the research community a way to organize and incorporate new knowledge about cities, urbanization and climate action. A fully articulated and implemented typology would allow researchers to link their city case study work to the case study work of other cities in order to determine connections amongst and across sets of cities and climate change conditions they face such as the identification and testing of policies for GHG emissions reduction and climate adaptation. In this way, the typology will help in the development of theoretically informed, meta-analyses of cities and urbanization and their connection to global climate change.

The typology could be used by a variety of individuals (e.g. data analysts, policy and program evaluators) user groups including interdisciplinary, intergovernmental research panels and programs (e.g. IPCC, Future Earth, UN Sustainable Development Goal process), city leadership alliances (e.g. C40), and non-profit organizations (e.g. ICLEI, UCCRN). As a specific example, the typology could directly connect to the new IPCC-related scenario process that establishes a framework for socioeconomic scenarios (i.e. Shared Socio-economic reference Pathways [SSP]) of climate change impact, adaptation, vulnerability, and mitigation research (O'Neill et al., 2014; Arnell et al., 2011; Moss et al., 2010). Several other examples for application among different potential user groups are noted in further detail below.

- *Graphic visualization of the climate change challenges* – The framework would help local decision-makers understand how their city compares with other cities. It is clear that some cities will face critical vulnerability challenges; others will be noted for their high levels of emissions, and still others will have both. The location of cities on the Emission-Vulnerability Plane could help a local decision-maker understand the factors leading to a high or low placement of their own or other cities by consulting the related Urbanization Characterization Matrix spider diagrams. The results also might help local managers identify other comparable city (perhaps those not typically or intuitively considered) facing similar issues from whom lessons might be learned or communication lines initiated.
- *Assessment of cities' climate change action trajectory* – The framework could provide a critical tool for understanding urban responses to climate change challenges over time by enabling a comparison of the current circumstances with past conditions of a given city or cluster of cities. The exploration of plausible trends could help understanding of what the future situation of a city might be, based on a combination of urbanization processes under-way and future climate scenarios downscaled for the city's location.
- *Prioritization tool for global actions and investments* – The framework can be used to guide global policy-makers, development agencies, and international associations of cities, researchers and opinion-makers decide which cities need the greatest support to face climate change challenges. This application will facilitate the allocation of concessional financing and technical assistance. For example, the typology could provide the Rockefeller Foundation additional information as it develops and executes its 100 Resilient Cities Campaign (100resilientcities.org) and the U.N. Climate Summit Compact of Mayors (un.org/climatechange/summit/).

In all these capacities, the typology should be useful for understanding the impacts of different mixes of policies directed at emissions or vulnerability reduction, and in turn will add knowledge regarding mitigation and adaptation intervention. Such policy portfolios will be based on the urban features and urbanization pathways defined in the typology, but also on scenarios and simulations of future climate and urbanization. They could be aimed at understanding the sensitivity of emissions and vulnerability conditions to changes in policies and create opportunities for achieving a less carbon-intensive and less vulnerable future for cities.

5. Conclusions

This paper introduces a framework to assess and illustrate the connection between urban areas, urbanization processes, and climate change. Several conditions are necessary for the successful development of a fully operational typology. The ongoing refinement and testing of the typology is an important component of its application and overall validity. Testing the validity of the conceptual framework on a large sample of cities can be performed as an on-going proof-of-concept exercise. This testing will allow understanding the appropriateness of different dimensions and indicators and their applicability to a range of cities.

Critical for typology implementation is a well-detailed procedure of how products were generated (e.g. which dimensions and indicators were used) and how the temporal and spatial contexts were derived. The use of the framework to examine individual, cohorts of cities (e.g. cities in one geographic region; low-lying coastal cities; rapidly growing cities), and fuller samples of cities will allow comparisons and inferences about the role of urbanization and urban governance processes including leverage points, policy packages, and behavioural shifts, as well as examination of a specific urban sector, such as transportation.

Developing UCM spider diagrams and ultimately linking them to emissions and vulnerability values hopefully can be important for decision makers who wish to use the typology to develop and evaluate policy interventions. With limited resources, in some cases, for instance, the typology might help reveal that it may be easier – less expensive, less-labor or resource intensive – to reduce exposure or sensitivity than to increase adaptive capacity which depends on such attributes as wealth, educational attainment, and robust emergency response systems. Similarly, GHG emissions reductions could be linked to urban development strategies that also will enable more sustainable and reliable resource provisions for residents and enhanced opportunities for resilience. Interconnections between the emissions and vulnerability indicators could simultaneously promote opportunities for climate change mitigation and adaptation.

A focus on reducing exposure may be a more effective short-term intervention than longer-term goals of increasing wealth and social capital, decreasing income inequalities, or mitigating both hazards and their drivers. Attention to the short-term, however, will imply trade-offs since increasing adaptive capacity or reducing GHG emissions can generate broader social benefits beyond the ability to cope with the hazards climate change is expected to aggravate. The key point is that identifying the elements of the urban vulnerability index gives decision makers an understanding of the levers for reducing vulnerability of their cities to climate change.

In this way, the range of practitioners and non-governmental agencies will find the typology useful for the development of global networking amongst urban stakeholders, to help identify and highlight issues of environmental justice for communities that lack political power to do this for themselves, and to enhance social group decision-making capacity. To do this work however, it must be recognized that access to high quality, comparable data is at the heart of the typology and its potential successful development. Data represent politically contested ground and city officials can be hesitant to gather or release data that might show their city in a negative light or reveal information that is felt to be proprietary. The discussion and analysis here has focused on data considered to be widely available for a large set of cities (although significant gaps are recognized to be present). To press the door open for more robust and meaningful comparative urban typology work, researchers and stakeholders must be able to access a greater sample of the data now being collected by cities and city networks (e.g., C40).

Appendix A. Emissions and Vulnerability variable data used in the sample application

Variable	Units	Unit description	Relationship to Vulnerability and Emissions V – vulnerability; E – emissions; V and E – both; A – adaptive capacity; X – unclear: the higher the value more associated with vulnerability or emissions
Demographic			
Total population	Millions of people		E
Age structure	Median age		E
Proportion of population who have migrated to city within last 5 years	% Migration in last 5 Years		V
Socio-Economic			
City income	US PPP/year		V and E
City income inequality	%	% of population below poverty level	V
Average years of education	Years		A

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Appendix A (*continued*)

Variable	Units	Unit description	Relationship to Vulnerability and Emissions V – vulnerability; E – emissions; V and E – both; A – adaptive capacity; X – unclear: the higher the value more associated with vulnerability or emissions
Schooling inequality by income and gender	Years		A
Institutions and governance			
Years since city incorporation	Years		A
Number of jurisdictions	Number of counties, municipalities, etc.		A
Measure of spatial centrality	Kilometers	Assumption – how close a given city is to a major economic center	X
Ecosystem and resources			
Water Availability	Liters per capita/day		V
Average Temperature	°C		X
Average Precipitation	Millimeters		X
Arable land	% of arable land (state)		V
Built environment, location, and land use			
Flood vulnerability	Index risk value	Based on Global Risk Data Platform (UNEP); and city income	V
Coastal vulnerability	Index risk value	Based on Nicholls et al. 2008	V
Total built land area	Square kilometers	City size	X
Fraction of population living in informal settlements	%	Percent living in slums	V
Local pollution – air quality	PM (ug/m^3)	Average annual particulate matter value	V
Vertical dimension of city	meters	Average altitude of city	X
Infrastructure			
Public transit	%	Within walking distance of 10 min	E
Transportation infrastructure	Kilometers	Subway or rail track extent	E
Transportation modes		Quantitative shares	X
GHG emissions	Millions tCOeq		E
energy consumption	TW h	National electricity consumption	E
Additional indicators			
Life expectancy	Years	Average for male and female	X
Population density	People per square kilometer		E
Proportion of state population residing in City	%		X

Appendix A (*continued*)

Variable	Units	Unit description	Relationship to Vulnerability and Emissions V – vulnerability; E – emissions; V and E – both; A – adaptive capacity; X – unclear: the higher the value more associated with vulnerability or emissions
Decadal growth	%		V and E
City contribution to national GDP	%		X
Sex ratio	Males per 1000 females		X
Percent workforce employed or looking for work actively	%		X
Proportion of households served by safe sanitation	%		V
Households with access to regular solid waste collection	%		V
Climate change action index	Index value	Based on existence of city plans	V and E
Disaster risk index	Index value	Based on economic value of a city and vulnerability	V
Percent wastewater treated	%		V
Percent households with access to safe and regular water supply	%		V
Death rate per 100,000 residents	Deaths Per 100,000 people		X
Household cellphone access	%		X
Percent households with adequate living conditions	%		V
Urban green space	%		V

Appendix B. References for emissions and vulnerability data

	Accra	Bangalore	Durban	Istanbul
Urban civilian workforce participation rate (employed and/or looking)	Ghana Living Standard Survey (GLSS 4)	Census of India, 2001 & 2011	IHS Global Insight Regional Explorer Southern Africa ,Regional Explorer v 674(2.5n), 2012	TUIK
Proportion of population living in slums and informal settlements	UN-Habitat, 2011	Rao, K.N. 2005. Poverty in India: Global and Regional Dimension. Deep & Deep Publications.	Statistics South Africa, CENSUS SA 1996,2001,2011	Istanbul Municipality Report
Annual total budget per capita		Sita Sekhar and Smita Bidarkar, Municipal	2001-Rans -U$$-EXCHANGE	

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Appendix B (*continued*)

	Accra	Bangalore	Durban	Istanbul
		Budgets in India: Comparison across Five Cities, EPW 1999+ Municipal Budgets	RATE R6.4486 at .3/.7/2000 2011-Rand – U$$-exchange rate R6.7308 at 1/7/11	
Death rate by violence per 100,000 inhabitants		http://ncrb.nic.in/CD-CII2012/Additional_Tables_CII_2012/Additional%20table%202012/DistrictWise%20IPC%20cases%20during%202001-2012.pdf	South African Police Services Crime Research and Statistics 2013	
Access to safe drinking	water/concentration of lead in drinking water supply	GSS, 2013	Census of India http://	
	www.censusindia.gov.in/2011census/hlo/District_Tables/Distt_table/29/HH2206-2900CRCD.pdf Bengaluru Portrait	Statistics South Africa, CENSUS SA 1996, 2001,2011	Türkiye Sağlıklı Kentler Birliği/ISKI	
Proportion of households served by safe sanitation services	GSS, 2014	Census of India http://www.censusindia.gov.in/2011census/hlo/District_Tables/Distt_table/29/HH2808-2900DCRC.pdf Bengaluru Portrait	Statistics South Africa, CENSUS SA 1996, 2001,2011	City Office, Health Ministry
Share of urban households with access to regular solid waste collection services	GSS, 2013	2013 = http://www.igidr.ac.in/pdf/publication/WP-2013-008.pdf	Statistics South Africa, CENSUS SA 1996, 2001,2011	TUIK/Municipality
Proportion of households with access to cell phones and high speed internet	GSS, 2013	Census of India http://www.censusindia.gov.in/2011census/hlo/District_Tables/Distt_table/29/HH4012-2900DCRC.pdf	Statistics South Africa, CENSUS SA 21996, 2001,2011	Bilişim Merkezi
Proportion of urban population living in adequate housing conditions	GLSS 4	Census of India http://www.censusindia.gov.in/2011census/hlo/District_Tables/Distt_table/29/HH0101-2900CRCD.pdf	Statistics South Africa, CENSUS SA 21996, 2001,2011	Türkiye Sağlıklı Kentler Birliği/TUIK
Climate change action index				
Disaster risk action index				
Urban green space	GIS Lab, University of Ghana	Greater Bangalore: Emerging Urban Heat Island, Ramachandra and Kumar, 2011		Istanbul Municipality Planning center

Appendix B (*continued*)

	Accra	Bangalore	Durban	Istanbul
Percentage of wastewater treated during regular operations, excluding extreme events	Huibers et al, 2003	2000 = N. Latha, N Deepa, B K Anand, K V Raju, H L Shashidhara, Wastewater Reuse in Megacities – Emerging Trends in Bangalore city 2010 = THE DECCAN BENGALURU – Bengaluru THE WATER-WASTE PORTRAIT 2015 = http://www.igidr.ac.in/pdf/publication/WP-2013-008.pdf		ISKI Performance reports 2011, 2013
Median age	Accra Metropolitan Assembly	Index Mundi	Statistics South Africa	LSE Cities
% Migration in last 5 years	Ghana Living Standard Survey (GLSS 5)	Institute for Social and Economic Change (ISEC)	eThekwini Municipality Integrated Development Plan 2014/2015	TUIK
City income		District Domestic Product Per Capita at Current Prices available for 1999 till 2005. Rest are projections made accordingly. http://planningcommission.nic.in/plans/stateplan/index.php?state=ssphdbody.htm	Constant 2005(Rand – U$$ exchange rate at 2005.01.07) IHS Global Insight	TUIK
City income inequality	UN-Habitat, 2011	Rao, K.N. 2005. Poverty in India: Global and Regional Dimension. Deep & Deep Publications.	IHS Global Insight Regional Explorer Southern Africa ,Regional Explorer v 674(2.5n), 2012	Turkish Statistics Institute (TUIK)
Years since city incorporation	City of Accra	Bangalore (Bengaluru) District : Census 2011 data	eThekwini/Durban City Population	The City of Istanbul – European Center of Culture
Number of jurisdictions	City of Accra	Bangalore (Bengaluru) District : Census 2011 data	eThekwini/Durban City Population	The City of Istanbul – European Center of Culture
Measure of spatial centrality	World Bank	World Bank	World Bank	World Bank
Water availability	Abraham et al. 2007	Mehta et al. 2013	IWA Water Wiki	Great Istanbul 2014
Average temperature	Climate Data	Climate data	Climate data	Climate data
Average precipitation	Climate data	Climate data	Climate data	Climate data
% Arable land	CIA World Fact Book	CIA World Fact Book	CIA World Fact Book	CIA World Fact Book
Flood risk vulnerability	Global Risk Data Platform (UNEP)	Global Risk Data Platform (UNEP)	Global Risk Data Platform (UNEP)	Global Risk Data Platform (UNEP)
Coastal risk vulnerability	Nicholls et al. 2008		Nicholls et al. 2008	Nicholls et al. 2008
Urban perimeter	UN-Habitat-Urban Profile	Index Mundi India	Census SA	Turkish Statistics Inst.

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Appendix B (*continued*)

	Accra	Bangalore	Durban	Istanbul
Air quality	Dionisio KL, Arku RE, Hughes AF, et al. Air pollution in Accra neighborhoods: spatial, socioeconomic, and temporal patterns. Environ. Sci. Technol. 2010;44(7):2270-2276.	Central Pollution Control Board India, Environmental Data Bank	South African Air Quality Information System, data received upon request (July 2013)	European Environment Agency. AirBase: public air quality database – air pollution.
Vertical dimension of city	Climatemps.com	Karnataka.com	KwaZulu Natal Climate and Weather, South Africa	Emporis
Transportation infrastructure		Bangalore Moobility Indicators – Draft http://www.indiaenvironmentportal.org.in/files/Draft%20Bangalore%20Mobility%20Indicators%202008.pdf	eThekwini Transport Authority Household Travel Survey Report 2009	
GHG emissions	Vanderpuije 2013	Bangalore Metro 2011	eThekwini Transport Authority Integrated Transport Plan Update 2014/2015	Istanbul-ulasim Raylı Sistemler
Energy consumption		World Bank	World Bank	World Bank
Population	International Energy Agency (IEA) 2013	IEA 2013	IEA 2013	IEA 2013
Decadal population growth	Ghana Statistical Service (GSS), 2013	Bangalore (Bengaluru) District : Census 2011 data	Census South Africa (SA)/ETA survey (IDP)	Turkish Statistics Inst./Ist.l Mun.
Sex ratio	GSS, 2013	Census of India 2011	Calculated	Turkish Statistics Inst.
	Accra	Bangalore	Durban	Istanbul
Mean life expectancy at birth	GSS, 2010 PHC Report	Bangalore (Bengaluru) District : Census 2011 data	Census SA	Turkish Statistics Inst.
City GDP	GSS, 2000 PHC Report	Index Mundi India	Statistics SA Mid-year population estimate, 2013 (KZN Life expectant, for Ethekwini, not available)	Turkish Statistics Inst.
City per capita income	Calculated with city authorities	Brookings Global Cities Initiative – Bangalore 2012	Constant 2005 prices(Rand –U$$ exchange rate at 2005.01.07) IHS Global Insight	Turkish Statistics Inst.
Proportion of national GDP	Ubaldo and Pescina (no date)	Brookings Global Cities Initiative – Bangalore 2012	Constant 2005 prices(Rand – U$$ exchange rate at 2005.01.07) IHS Global Insight	Turkish Statistics Inst.
Area	UN-Habitat-Urban Profile	Bangalore (Bengaluru) District : Census 2011	Census SA	Turkish Statistics Inst.

Appendix B (*continued*)

	Accra	Bangalore	Durban	Istanbul
Population density	Ghana Statistical Service 2010 PHC	Bangalore (Bengaluru) District : Census 2011 data	Calculated	Turkish Statistics Inst./Ist.l Mun.
Proportion of state population	GSS	Index Mundi India	Census SA	Turkish Statistics Inst.
Land use	GIS Lab, University of Ghana 2014	Bruhat Bengaluru Mahanagara Palike	Ethekwini IDP 2002 and 2005	Azime Tezer, 2013

	New York	Rio de Janeiro	Freiburg	Boise	Kampala
Urban civilian workforce participation rate (employed and/or looking)	2012 Bureau of Labor Statistics. 2000 US Census SF3 and ACS 5-Yr survey, 2006–2010. For the population age 16 and over.	IBGE | Data for RJMA	EuroStat	2011–2013 American Community Survey	Urban Labor Force Survey Report 2009
Proportion of population living in slums and informal settlements	ACS 5-Yr survey, 2006–2010 and Census 2000 SF3. Housing Units lacking complete plumbing facilities.	IBGE | Data for the City Rio		City of Boise	World Bank
Annual total budget per capita	NYC Office of Management and Budget. FY 2009 and FY 2002 Adopted Budgets. Calculated Budget/Population.	City Hall; IPP; Penn World Table	Calculated	Calculated	Calculated
Death rate by violence per 100,000 inhabitants	NYPD Crime Statistics	IBGE | Rio		City-Data.com	Uganda Demographic Profile 2014
Access to safe drinking water/concentration of lead in drinking water supply	New York City Department of Environmental Protection	IPEA (Instituto de Pesquisa Econômica Aplicada)	EuroStat	City of Boise	Uganda Demographic Profile 2014
Proportion of households served by safe sanitation services	US Census – 1990, 2000 and 2006-2010 ACS 5 yr average	IPEA	EuroStat	City of Boise	Uganda Demographic Profile 2014
Share of urban households with access to regular solid waste collection services	New York City Department of Sanitation	IPEA	EuroStat	City of Boise	World Health Organization; UNICEF
Proportion of households with access to cell phones and high speed internet	PEW; Broadband Advisory Committee	IBGE	EuroStat		

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Appendix B (*continued*)

	New York	Rio de Janeiro	Freiburg	Boise	Kampala
Proportion of urban population living in adequate housing conditions	Number of homeless persons as a percent of the total population. Homeless Outreach Population Estimates (HOPE) was conducted annually starting in 2003. The 2000 estimate is from the 2003 HOPE Census.	IBGE	EuroStat	City of Boise	Mukiibi, S. (2012). The effect of urbanisation on the housing conditions of the urban poor in Kampala, Uganda. In Second international conference on advances in engineering and technology, 20th–21st December, Noida, India. http://mak.ac.ug/documents/Makfiles/aet2011/Mukiibi.pdf. Accessed (Vol. 3).
Climate change action index	City of New York				
Disaster risk action index	City of New York				
Urban green space	NYC Open Space				
Percentage of wastewater treated during regular operations, excluding extreme events	Department of Environmental Protection		EuroStat	City of Boise	Ministry of Water and Environment 2011
Median age	Department of City Planning, New York City, 2013	DATA Rio	EuroStat	US Census 2012	Uganda Demographic Profile 2014
% Migration in last 5 years	Department of City Planning, New York City, 2013	Brookings Global Cities Initiative		US Census 2012	Uganda Demographic Profile 2014
City income	Calculated	CEPERJ and Penn World Table	EuroStat	US Census 2012	CIA 2013
City income inequality	1990, 2000, and 2010 US Census. Measured as percent of the US population with income below the poverty level.	IBGE (Instituto Brasileiro de Geografia e Estatística)	Knoema – Regional Poverty and Social Exclusion Statistics	US Census 2012	Poverty in Kampala, Uganda – The Borgen Project
Years since city incorporation	City of New York	Rio de Janeiro City Population	Encyclopedia Britannica	City-Data.com	Kampala City – The Information
Number of jurisdictions	City of New York	Rio de Janeiro City Population	Encyclopedia Britannica	City-Data.com	Kampala City – The Information

Appendix B (*continued*)

	New York	Rio de Janeiro	Freiburg	Boise	Kampala
Measure of spatial centrality	World Bank	World Bank	World Bank	World Bank	World Bank
Water availability	NYC DEP 2014	Siemens	INNOVATION NETWORK MORGENSTADT: CITY INSIGHTS	U.S. Geological Survey	Uganda Demographic Profile 2014
Average temperature	NOAA 2014	Climate data	Climate data	Climate data	Climate data
Average precipitation	NOAA 2014	Climate data	Climate data	Climate data	Climate data
% Arable land	CIA World Fact Book	CIA World Fact Book	CIA World Fact Book	CIA World Fact Book	Kampala, Urban Study Land Use Map
Flood risk vulnerability	Global Risk Data Platform (UNEP)	Global Risk Data Platform (UNEP)	Global Risk Data Platform (UNEP)	Global Risk Data Platform (UNEP)	Global Risk Data Platform (UNEP)
Coastal risk vulnerability	Nicholls et al. 2008	Nicholls et al. 2008			
Urban perimeter	US Census	IBGE Cidades, IPEADATA	Encyclopedia Britannica	US Census 2012	Uganda Demographic Profile 2014
Air quality	US EPA Particulate Matter National Trends, US EPA, 2013	Instituto Brasileiro de Geografia e Estatistica	European Environment Agency	US EPA Particulate Matter National Trends, US EPA, 2013.	Schwander, S., Okello, C.D., Freers, J., Chow, J.C., Watson, J.G., Corry, M., & Meng, Q., (2014). Ambient Particulate Matter Air Pollution in Mpererwe District, Kampala, Uganda: A Pilot Study. Journal of environmental and public health, 2014.
Vertical dimension of city	NYS GIS Clearinghouse	Info Escola	Germany Insider Facts	US climate data	Encycloedia Britannica Online
Public transit	New York City Department of Transportation		Buehler, R. and Pucher, J. (2010). Sustainable Transport in Freiburg: Lessons from Germany's Environmental Capital. International Journal of Stustainable Transport, in press.	2011-2013 American Community Survey	

(*continued on next page*)

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Appendix B (*continued*)

	New York	Rio de Janeiro	Freiburg	Boise	Kampala
Transportation infrastructure	NYC department of transportation	Metro Rio	Buehler, R. and Pucher, J. (2010). Sustainable Transport in Freiburg: Lessons from Germany's Environmental Capital. International Journal of Stustainable Transport, in press.	Brookings Institute	Transportation in Kampala
GHG emissions	PlaNYC 2013	World Bank	C40 Cities – Freiburg		World Bank
Energy consumption	IEA 2013	IEA 2013	IEA 2013	IEA 2013	Uganda General Operating Environment
Population	1990, 2000, and 2010 US Census.	IBGE Cidades@, IBGE Censo 2010 Sinopse, IBGE (Instituto Brasileiro de Geografia e Estatística) and IPP (Instituto Pereira Passos)	EuroStat	US Census 2012	Kampala City – The Information
Decadal population growth	1990, 2000, and 2010 US Census. Calculated from population numbers.	IBGE Cidades@, IBGE Censo 2010 Sinopse, IBGE and IPP			Uganda Demographic Profile 2014
Sex ratio	1990, 2000, and 2010 US Census. Calculated.	IPEADATA and IBGE for projection	EuroStat	US Census 2012	Uganda Demographic Profile 2014
Mean life expectancy at birth	US Census and Preston and Elo (2014)	IPEADATA and IBGE	EuroStat	US Census 2012	Uganda Demographic Profile 2014
City GDP	*2001* and 2010 Bureau of Economic Analysis. Values are for the New York Metro area.	IPP	EuroStat	US Census 2012	Poverty in Kampala, Uganda – The Borgen Project
City per capita income	US Census. For 2010, per capita money income in past 12 months (2012 dollars), 2008-2012.	Pen World Table and CEPERJ	Calculated	Calculated	Calculated
Proportion of national GDP	1990, 2000, 2010 Bureau of Economic Analysis	IPP	Calculated	Calculated	World Bank

Appendix B (*continued*)

	New York	Rio de Janeiro	Freiburg	Boise	Kampala
Area	US Census	IBGE Cidades, IPEADATA	UrbiStat	City-Data.com	Uganda Demographic Profile 2014
Population density	Calculated	IBGE Cidades	UrbiStat	City-Data.com	Uganda Demographic Profile 2014
Proportion of state population	US Census/calculated	IBGE Censo 2010 Sinopse	Calculated	Calculated	Calculated
Land use	NYC Department of City Planning	IPP		City of Boise	Kampala, Urban Study Land Use Map

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