Experiences of integrated assessment of climate impacts, adaptation and mitigation modelling in London and Durban

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ABSTRACT   The urgent need to reconfigure and transform urban areas to consume fewer resources, emit less pollution, minimize greenhouse gas production, protect natural ecosystems and increase the adaptive capacity to deal with climate risks is widely recognized. The implementation of improved sustainability measures in cities requires integrated thinking that encompasses a whole range of urban functions, often implying a major restructuring of urban energy systems, transport and the built environment, as well as a new approach to the planning and management of natural systems that service urban areas. Many local governments have a limited capacity to deal with such complex and interrelated problems, and this hampers their ability to deal with climate change. With these issues in mind, teams of scientists, practitioners and stakeholders in Durban (led by eThekwini Municipality) and London (led by the Tyndall Centre for Climate Change Research) developed city-scale integrated assessment modelling tools that represent interactions between different urban functions and objectives by linking climate change issues to broader agendas such as spatial planning. This paper reviews each integrated assessment tool, and critically analyzes their effectiveness in terms of technical approach, extent to which they meet policy needs, role of stakeholders in model development and application, barriers to their uptake and the value of and effort required for integration. While these integrated assessment tools did not provide the detailed design information sought by some decision makers, importantly they have stimulated stakeholders to think strategically and hold cross-sectoral conversations around implementing sustainability measures. Despite the technical and institutional challenges associated with the development and uptake of an integrated assessment model, we conclude that they do contribute to the quest for urban sustainability.

KEYWORDS adaptation / climate change / decision-making / integrated assessment / local government

I. INTRODUCTION AND BACKGROUND

It is widely recognized that the high concentrations of people, infrastructure and economic activity in urban areas make them contributors of global greenhouse gas emissions and hotspots of vulnerability to climate impacts. Climate impacts in urban areas include sea level rise, flood risk, building and infrastructure damage, water availability, urban heat island

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effect and biodiversity impacts[1] – as well as some that are unique to cities, for example overheating of underground transportation systems[2] – and these need to be considered alongside issues like the urban econony and resource flows. Furthermore, urban areas require energy-intensive services such as transportation, heating or cooling, industrial processes, water supplies, etc. Sources have suggested that as much as 80 per cent of global greenhouse gas (GHG) emissions[3] and 71 per cent of global energy-related carbon emissions can be attributed to urban areas,[4] although it is likely that, worldwide, less than half of anthropogenic GHG emissions are generated within city boundaries.[5] It is therefore not surprising that cities are considered "first responders" to climate change through local adaptation and mitigation measures.[6]

Considering climate change issues at the city scale is important and globally strategic for a number of reasons, not least of which is the fact that the urban population is estimated to reach 6.3 billion by 2050,[7] with the bulk of this growth taking place in small to medium cities of the global South[8] that have little institutional capacity to address issues of climate change. Larger and more prosperous cities also direct global consumption and production. Because cities are decision-making centres, they are places where governance systems interact directly with people and, as such, they provide ideal opportunities for immediate and direct action for adaptation *and* mitigation. This is evident in the range of climate initiatives already taking place at the city scale.[9] For example, mitigation action is being undertaken through the C40 Large Cities Leadership Group, the ICLEI–Local Governments for Sustainability's Cities for Climate Protection Programme, the Mexico City Pact and Europe's Covenant of Mayors; while the Rockefeller Foundation's Asian Cities Climate Change Response Network (ACCCRN) and the Durban Adaptation Charter, championed by eThekwini Municipality and a South African local government partnership that includes ICLEI–Local Governments for Sustainability (signed by 107 mayors representing more than 950 cities at COP17–CMP7), are examples of an emerging and growing local level mobilization around the issue of adaptation. Urban administrations are also conducting their own climate change impact studies[10] (for example, London Mayor's Climate Change Adaptation Strategy[11] and Durban's Municipal Climate Protection Programme),[12] which bring together key stakeholders to facilitate decision-making in relation to adaptation at an appropriate level of governance.[13]

Spatial configuration of urban areas and how land is used and developed has significant implications for adaptation to climate change[14] and the reduction of GHG emissions.[15] Energy use and GHG emissions in a city are dependent on urban form and design. Similarly, many adaptation responses, such as protecting upper catchment areas to ensure water security and ensuring the survival of coastal mangroves as a barrier against storm surges, involve land use and land management decisions. It may not always be possible, however, to reduce vulnerability, in particular in coastal cities that are at risk from sea level rise,[16] and thus as cities continue to grow, location and density of development become increasingly important. Urban sprawl could lead to populations becoming reliant on private modes of transportation to travel to work, and growth that impacts on the local level biodiversity. Similarly, growth of informal settlements could lead to other issues linked to ecological sustainability and human well-being, for example water pollution, biodiversity loss, fuel

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1. Dawson, Richard J (2007), "Re-engineering cities: a framework for adaptation to global change", *Philosophical Transactions Series A, Mathematical, Physical and Engineering Sciences* Vol 365, No 1861, pages 3085–3098; also Wilby, Robert L (2007), "A review of climate change impacts on the built environment", *Built Environment* Vol 33, No 1, pages 31–45; and Hunt, Alistair and Paul Watkiss (2011), "Climate change impacts and adaptation in cities: a review of the literature." *Climatic Change* Vol 104, No 1, pages 13–49.

2. Lindley, Sarah J, John F Handley, Nicolas Theuray, Elizabeth Peet and Darryn McEvoy (2006), "Adaptation strategies for climate change in the urban environment: assessing climate change-related risk in UK urban areas",

Journal of Risk Research Vol 9, No 5, pages 543–568.

3. O'Meara, Molly (1999), *Reinventing Cities for People and the Planet*, Worldwatch Paper 147, Washington DC, 94 pages.

4. IEA (2008), *World Energy Outlook 2008*, International Energy Agency, OECD, Paris, 578 pages.

5. Satterthwaite, David (2008), "Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions", *Environment and Urbanization* Vol 20, No 2, October, pages 539–549.

6. Rosenzweig, Cynthia, William Solecki, Stephen A Hammer and Shagun Mehrotra (2010), "Cities lead the way in climate change action", *Nature* Vol 467, No 7318, pages 909–911.

7. UN (2010), *World Urbanization Prospects: the 2009 Revision; Highlights*, United Nations, New York, 56 pages.

8. UN–Habitat (2011), *Cities and Climate Change: Global Report on Human Settlements 2011*, United Nations Human Settlements Programme, Earthscan, London, 279 pages.

9. Castán Broto, Vanesa and Harriet A Bulkeley (2012), "A survey of urban climate change experiments in 100 cities", *Global Environmental Change* Vol 23, No 1, pages 92–102.

10. ARUP (2011), "Climate action in megacities: C40 cities baseline and opportunities", launched as part of C40 Cities Climate Leadership Summit in São Paulo, 31 May–2 June 2011; also Carbon Disclosure Project (2011), "CDP cities 2011: global report on C40 cities", *C40 Cities Climate Leadership Group and Carbon Disclosure Project* (CDP), London, UK, 40 pages; Carmin, JoAnn, Nikhil Nadkarni and Christopher Rhie (2012), "Progress and challenges in urban climate adaptation planning: results of a global survey", MIT, Cambridge MA, 33 pages; and Heidrich, Oliver, Richard Dawson, Diana Reckien, Claire Walsh (in press), "Assessment of the climate preparedness of 30 urban areas in the UK", *Climatic Change*, doi 10.1007/s10584-013-0846-9.

poverty and an increased burden of disease. It is at the local level of cities (i.e. economic and political centres), managed by local governments and city administrations, that many key spatial planning decisions are made.

Implementation of any policy or measure has potential for knock-on effects. This is true of mitigation and adaptation activities that can enhance or conflict with other sustainability objectives. These can be particularly acute in cities where interactions and interdependencies between infrastructure and people are especially dense. Understanding these potential trade-offs contributes to a more integrated climate policy.[17] For example, compact settlements may reduce energy demand and transport emissions, yet the increase in built mass would intensify the urban heat island effect and pose problems for urban drainage by reducing the coverage of natural ecosystems and the services they supply. Intensification of the urban heat island effect, amplified by hotter summers in many parts of the world, could drive up the demand for air-conditioning or encourage city dwellers to relocate and commute from cooler rural locations; both would increase greenhouse gas emissions. Conversely, the use of green and blue spaces in urban design can mitigate the impacts of urban heat and pluvial flooding as well as provide opportunities for sequestering carbon.[18] However, these need to be strategically planned and managed to maximize their functionality.[19]

Cities are complex spaces, embracing a large number of stakeholders, different interest groups and varying ecologies that cannot be considered in isolation. Physical and political boundaries are seldom respected by resource flows, for example the importation of food from rural areas or the exportation of waste out of urban areas. Changes that take place within or outside any boundary can have a profound effect on the other. It is this complexity, across the spectrum of social, engineered and ecological systems, that may inhibit integrated "climate smart" strategies being implemented for infrastructure development or land use planning.[20] It is important to address this challenge, as the effective delivery of integrated planning and management systems would ensure that the combined effect of local efforts would be more beneficial than that of any individual agency or organization acting in isolation. Hall[21] also recognizes that uncertainties in climate science and other long-term changes such as demography pose further challenges for urban planners.

Integrated assessment (IA) assimilates a range of knowledge streams from different sectors and disciplines to facilitate interpretation, communication, decision-making and learning around complex issues and systems. An IA may provide qualitative insights or, as presented here, quantified outputs across multiple sectors and their interactions. Quantified integrated assessment methods add numbers to identified interactions and offer a means to address these challenges by bringing together an understanding of multiple urban functions to support decision-making at the city level. IA methods have been successfully implemented globally and nationally[22] to assess long-term climate policies with social actors in terms of climate change impact targets, mitigation costs and implementation methods. At the regional level,[23] IA methods have developed hydrodynamic, morphological, reliability and socioeconomic models over a large spatial and extended temporal scale for analysis of coastal management practices and climate and socioeconomic changes in East Anglia, UK. A whole-system approach incorporates the complexities and interactions of the various components, allowing

future scenarios of climate and socioeconomic change to be explored and different policy options to be tested in a common framework. With such promise, it is hardly surprising that a number of city-scale IA tools have begun to emerge. IAs may take the form of a single unified model but, as in the case of the two presented in this paper, loosely connected models representing different components of the urban system are driven by a consistent set of climate and socioeconomic scenarios. This paper summarizes experiences from two mature urban integrated assessment modelling programmes for the cities of London (UK) and Durban (South Africa). The development of their IA tools took place at a similar time, and following a meeting between the two project leaders at an international conference, a collaboration between the two development teams and cities was agreed to. The two cities, their challenges and their approach to IA are briefly described and compared before highlighting the benefits, challenges and barriers to the application and uptake of the IA tools by decision makers and stakeholders. The paper concludes with thoughts on the utility of urban-scale IA and recommendations for urban areas wishing to undertake IA studies in the future.

II. REVIEW AND COMPARISON OF INTEGRATED ASSESSMENT MODELS

a. The Urban Integrated Assessment Facility (UIAF) for London

London, the Tyndall Centre case study, has a population of 8.2 million, which is expected to grow by more than one million over the next two decades.[24] It is the largest city in Europe with an economic influence that dominates England, and is located at the hub of the UK's transport networks. It has a highly diversified economy with an emphasis upon the service sectors, especially banking, financial services, consultancy and government administration, and is a global hub for banking, finance and commerce. London is, however, becoming an increasingly polarized city, with pockets of poverty and deprivation in the inner north-east and towards the east of the city, tending to affect predominantly Black, Asian and ethnic minority groups.[25] Potential impacts of climate change in London include flood risk (15 per cent of the city is located on the floodplain), water shortages (London's annual total rainfall is 30 per cent of the UK's average and there is increasing demand from an increasing population), excessive urban temperatures and air quality problems (due to its geographical location and widespread urbanization), windstorms and subsidence.

In 2006, the Tyndall Centre for Climate Change Research launched its second phase of funded research, which included a new programme on climate change and cities. Building upon the Tyndall Centre's track record in integrated assessment modelling at global[26] and local[27] scales, this programme aimed to develop a quantified integrated assessment model for analyzing both the impacts of climate change in cities and their greenhouse gas emissions.

Figure 1 shows the structure of the Urban Integrated Assessment Facility (UIAF) developed for London. Considering climate change in cities is a long-term and complex challenge that requires a framework that incorporates a range of social, economic and environmental functions

11. GLA (2011a), "Managing risks and increasing resilience. Mayor's climate change adaptation strategy", Mayor of London, October 2011, Greater London Authority, London, 125 pages.

12. Roberts, Debra (2008), "Thinking globally, acting locally – institutionalizing climate change at the local government level in Durban, South Africa", *Environment and Urbanization* Vol 20, No 2, October, pages 521–537.

13. See reference 1, Hunt and Watkiss (2011).

14. Hurlimann, Anna and Alan March (2012), "The role of spatial planning in adapting to climate change", *Climate Change* Vol 3, No 5, Wiley Inter-disciplinary Reviews, pages 477–488.

15. Lindley, Sarah J, John F Handley, Darryn McEvoy, Elizabeth Peet and Nicolas Theuray (2007), "The role of spatial risk assessment in the context of planning for adaptation in UK urban areas", *Built Environment* Vol 33, No 1, pages 46–69.

16. Nicholls, Robert J, Susan Hanson, Celine Herweijer, Nicola Patmore, Stéphane Hallegatte, Jan Corfee-Morlot, Jean Château and Robert Muir-Wood (2008), "Ranking port cities with high exposure and vulnerability to climate extremes: exposure estimates", OECD Environment Working Paper No 1, OECD, Paris, 62 pages.

17. See reference 1, Dawson (2007).

18. McEvoy, Darryn, Sarah J Lindley and John F Handley (2006), "Adaptation and mitigation in urban areas: synergies and conflicts", *Proceedings of the Institution of Civil Engineers: Municipal Engineer* Vol 159, No 4, pages 185–191.

19. Gill, Susannah E, John F Handley, A Roland Ennos, Stephan Pauleit, Nicolas Theuray and Sarah J Lindley (2008), "Characterizing the urban environment of UK cities and towns: a template for landscape planning", *Landscape and Urban Planning* Vol 87, No 3, pages 210–222.

20. See reference 1, Dawson (2007).

21. Hall, Jim W (2009), "Integrated assessment to support regional and local decision-making", in Simin Davoudi, Jenny Crawford and Abid Mehmood, *Planning for Climate Change. Strategies for Mitigation and Adaptation for Spatial Planners*, Earthscan, London, pages 236–246.

22. See, for example, Toth, Ferenc L, Thomas Bruckner, Hans-Martin Füssel, Marian Leimback and Gerhard Petschel-Held (2003a), "Integrated assessment of long-term climate policies: Part 1 – model presentation", *Climatic Change* Vol 56, No 1–2, pages 37–56; also Toth, Ferenc L, Thomas Bruckner, Hans-Martin Füssel, Marian Leimback and Gerhard Petschel-Held (2003b), "Integrated assessment of long-term climate policies: Part 2 – model results and uncertainty analysis", *Climatic Change* Vol 56, No 1–2, pages 57–72.

23. See, for example, Dawson, Richard J, Mark E Dickson, Robert J Nicholls, Jim W Hall, Mike J A Walkden, Peter K Stansby, Mustafa Mokrech, Julie Richards, Jianguo Zhou, Jessica Milligan, Andrew Jordan, Steve Pearson, John Rees, Paul Bates, Sotiris Koukoulas and Andrew R Watkinson (2009), "Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long-term change", *Climatic Change* Vol 95, No 1, pages 249–288.

24. GLA (2011b), "The London Plan. Spatial development strategy for greater London", Mayor of London, July 2011, Greater London Authority, 343 pages.

25. See reference 24.

26. Arnell, Nigel W and Tim Osborn (2006), "Interfacing climate and impacts models in integrated assessment modelling", Tyndall Centre for Climate Change Research, Technical Report 52, 63 pages.

27. See reference 23.

28. Goodess, Clare M, Jim W Hall, Martin Best, Richard Betts, Laure Cabantous, Phil D Jones, Chris G Kilsby, Alan Pearman and Craig Wallace (2007), "Climate scenarios
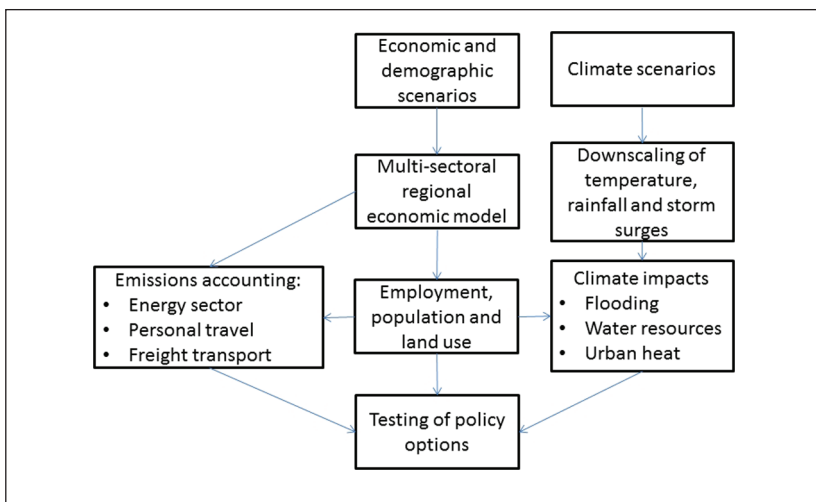
FIGURE 1
Overall structure of the Urban Integrated Assessment Facility (UIAF)

SOURCE: Based on Walsh, Claire L, Richard J Dawson, Jim W Hall, Stuart L Barr, Mike Batty, Abigail L Bristow, Sebastian Carney, Athanaseous S Dagoumas, Alistair C Ford, Colin Harpham, Miles R Tight, Helen Watters and Alberto M Zanni (2011), "Assessment of climate change mitigation and adaptation in cities", *Proceedings of the Institution of Civil Engineers: Urban Design and Planning* Vol 164, No 2, pages 75–84.

and responses. Context for the analysis is provided by socioeconomic and climate scenarios,[28] which through a process of downscaling generate economic and demographic scenarios for the urban area and climate scenarios at the city scale, and set the boundary conditions for the analysis. The land use module provides high resolution spatial scenarios of population and land use that form the basis of the emissions and climate impact vulnerability analysis. Modules for emissions accounting and climate impact assessments are assessed under a range of climate, socioeconomic and technological change scenarios. The UIAF has the flexibility to test a wide range of adaptation and mitigation policies such as land use planning, alterations to the transport systems, changes in energy technologies and measures to reduce climate risks. It has been applied to three of the GLA's[29] priority risks of flooding, heat waves and water availability, but provides a platform upon which other climate issues, for example air quality, health and biodiversity, could be analyzed. The various modules are brought together in an IA where relevant information is passed between each module (for example, census ward population projections from the land use model are passed to the climate impacts models to evaluate risks). Figure 2 (on page 366) presents illustrative outputs from the model – in this case, expected annual damage from flooding[30] in 2005 and two future (2100) development scenarios are compared. The benefits of different adaptation options in terms of reductions in expected annual damage can be explored to allow decision makers to identify appropriate policies to manage flood risk (Figure 3).
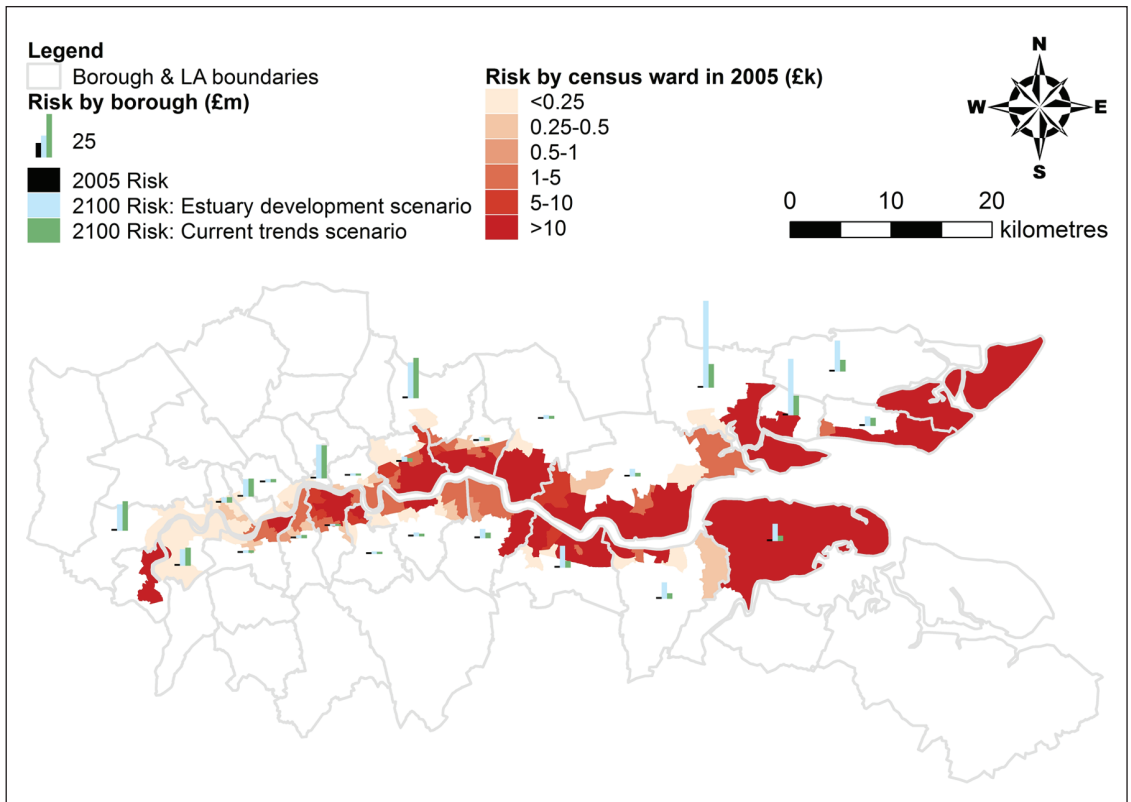
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FIGURE 2
Expected annual damage from flooding, comparing the 2005 flood risk with flood risks in 2100 from a "current trends" land use scenario with an "estuary development" scenario, where the Olympic Park in Stratford and the East London Docklands financial district become major drivers of London's growth, leading to the majority of development and land use change over the coming century to take place along the Thames Estuary corridor.

SOURCE: Authors' own analysis.

Throughout the research programme there was regular interaction with stakeholders, including analysis of the land use planning and transport infrastructure proposed in the London Plan.[31] Specifically, in developing the London Plan, the GLA needed to consider a range of different development scenarios, providing quantified evidence of the benefits or limitations of each; the UIAF provided the opportunity to conduct this analysis.

b. The integrated assessment tool for Durban

Durban is a culturally diverse South African city of 3.5 million people located in the province of Kwazulu Natal. It has the largest port on the east coast of Africa and is a key manufacturing centre. As with many African cities, it faces a range of serious socioeconomic challenges, including high

and decision-making under uncertainty", *Built Environment* Vol 33, No 1, pages 10–30.

29. See reference 11.

30. Dawson, Richard J, Tom Ball, Jonathan Werritty, Alan Werritty, Jim W Hall and Nicolas Roche (2011), "Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socioeconomic and environmental change", *Global Environmental Change* Vol 21, No 2, pages 628–646.
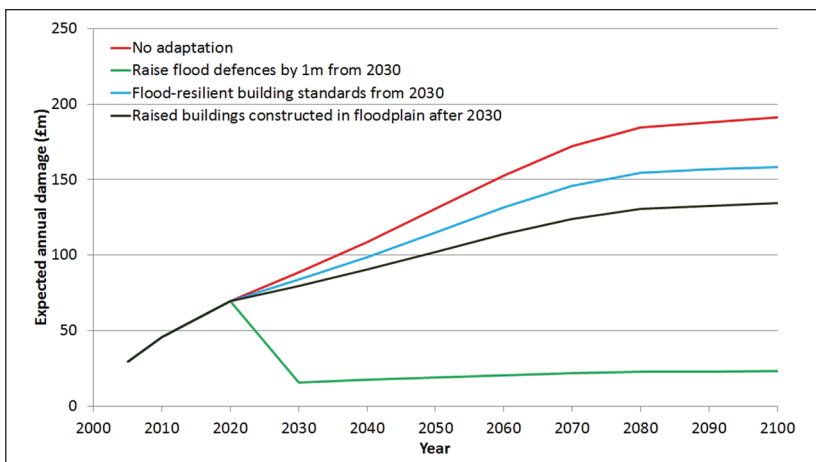
31. See reference 24.

FIGURE 3

Expected annual damage from flooding for the "estuary development" scenario under the UKCP09 medium climate change scenario over time, and the damage reduction benefits of a number of adaptation options implemented in 2030.

SOURCE: Authors' own analysis.
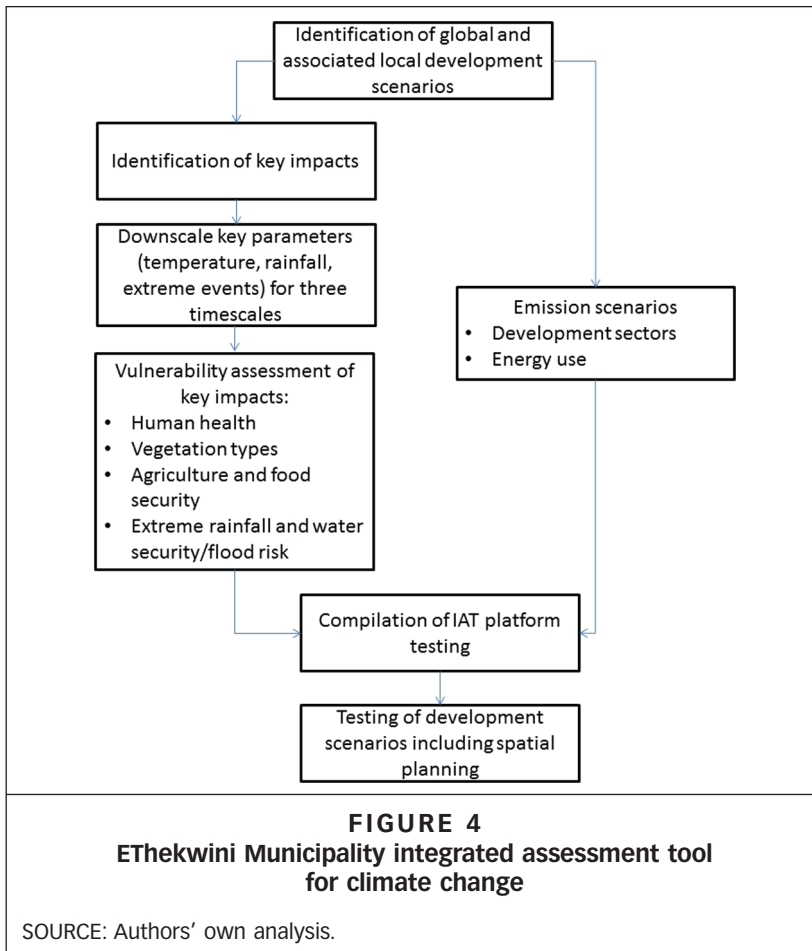
32. See reference 12.

33. Roberts, Debra (2010), "Prioritizing climate change adaptation and local level resilience in Durban, South Africa", *Environment and Urbanization* Vol 22, No 2, October, pages 397–413.

34. See reference 12; also see reference 33.

35. EThekwini Municipality (2012), *Integrated Development Plan, Five Year Plan: 2012–2013 to 2016–2017,* 331 pages.

levels of poverty, unemployment and HIV-Aids infection rates, and large infrastructural backlogs.[32] Mimicking national trends, there is a widening gap between the advantaged and disadvantaged elements of society. These challenges are magnified by Durban's location within one of 34 global biodiversity hotspots. As a result, the development objectives of the city have to be pursued within an area where globally significant biodiversity is already under threat from extensive habitat loss. This undermines the city's long-term adaptive capacity through the loss of critical ecosystem services.[33] Durban therefore provides the arena where tensions between rich and poor, inclusion and exclusion, development and environment pose significant challenges to the achievement of integrated planning and the likelihood of achieving sustainability and improved levels of climate protection. In response to these challenges, eThekwini Municipality (the local government responsible for managing the city of Durban) initiated the development of a Municipal Climate Protection Programme in 2004.

The Durban programme (schematic shown in Figure 4 on page 368) focused on understanding the possible impacts of climate change on Durban and developing appropriate (largely adaptation) responses.[34] For example, Figure 5 on page 369 shows the results of an analysis of how temperature may affect agricultural yield. Because of the complexity and range of likely impacts, and the challenges of existing climate variability and poverty and underdevelopment, it was clear that making the city "climate smart" would involve difficult and strategic choices. These choices will have a significant bearing on achieving the development objectives captured in the city's key strategic planning document known as the Integrated Development Plan.[35] The Durban IA tool was commissioned in order to facilitate a better understanding of the available data, enable

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FIGURE 4
**EThekwini Municipality integrated assessment tool
for climate change**

SOURCE: Authors' own analysis.

interrogation of climate change impacts and help prompt discussions around suitable responses. The idea was to provide a means for local level decision makers to evaluate and compare strategic development plans in the context of climate change, and to interrogate issues such as land use conflicts and interactions (for example, prime agricultural land overlapping with important biodiversity areas), identify areas of priority and vulnerability, particularly with regard to vulnerable communities and protection of infrastructure, as well as the potential opportunities for economic growth presented by climate change effects.[36] Although the work was inspired in part by eThekwini Municipality's interaction with the Tyndall Centre, the tools differ substantially. The London IA simulates future scenarios of land use and other drivers of change, whereas the Durban equivalent "… *facilitates climate change impact visualization and assessment.*"[37] This approach was more applicable to the Durban setting due to limited data availability as well as the priorities of the local government client who wanted access to the tool and its outputs. The aim, therefore, was for the Durban IA tool to be accessible to users not familiar with the basics of climate change science and who were likely to be challenged by the analysis of complex data sets.

36. Golder Associates (2010), "EThekwini Municipality integrated assessment tool for climate change", Report prepared for eThekwini Municipality, Report Number 10290-9743-13, Durban, South Africa, 63 pages.
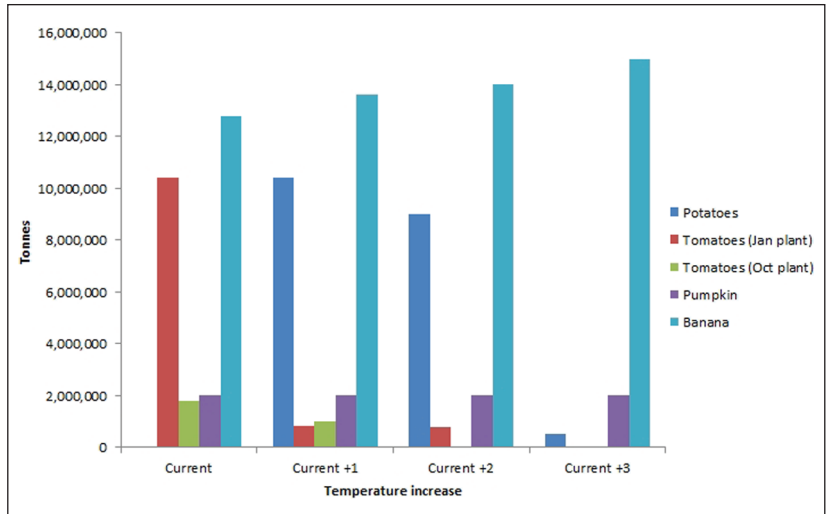
37. See reference 36, page 2.

FIGURE 5
Bio-resource unit projections for how a change in temperature may affect crop yield for potatoes, tomatoes, pumpkins and bananas

SOURCE: Authors' own analysis.

The final version of Durban's IA tool consists of a document viewer and a GIS viewer. The document viewer provides access to key documents associated with the Municipal Climate Protection Programme and information on climate change. The GIS viewer "… *is a stand-alone mapping application that allows the user to view geo-referenced data within the municipality.*"[38] The data comprise city "base data" such as roads, maps, area names, open space system plan, informal settlement plan, etc., as well as climate change projection data, including basic meteorological projections (temperature, rainfall) and projections of changes, from models, in agricultural crop yields, extreme rainfall events, vegetation type distribution and health. The majority of these data were represented spatially at the city level for the first time, and the intention was to make that information accessible to a broader audience. Figure 6 on page 370 presents a sample output map of the maximum yield potential of soybean in the intermediate future, and indicates that future favourable areas for cultivation are in those parts of the city where the most significant biodiversity resources – which are key to the city's ecosystem-based adaptation strategy – still exist.

38. See reference 36, page 44.

c. Integrated assessment tools: challenges and barriers for decision makers

Table 1 on page 371 provides an overview of the two tools. Both cities are growing and are subject to a range of climate-related risks, but in addition Durban faces issues of vector-borne diseases, biodiversity loss
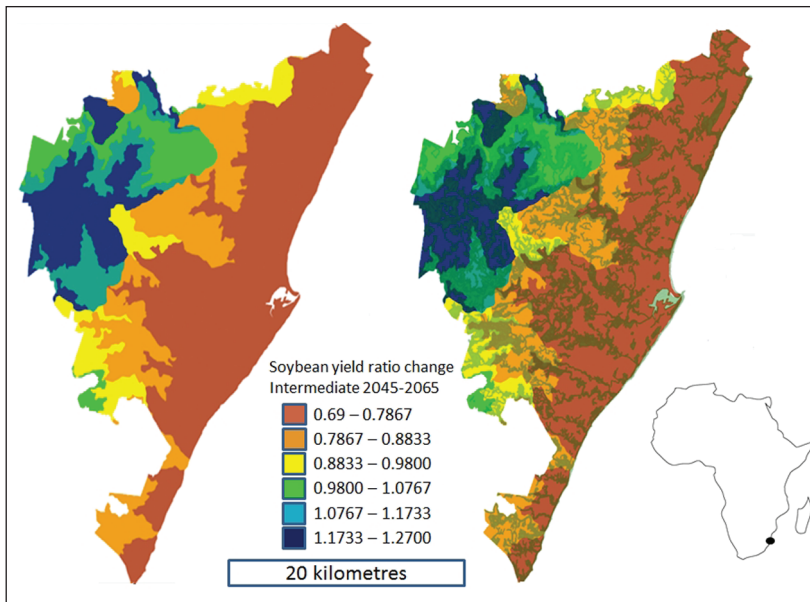
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FIGURE 6

Maximum yield potential of soybean in the intermediate future within Durban

NOTE: "Warmer" (brown and orange) colours show a noticeable decrease in coastal productivity to sub-optimal levels. The figure on the right clearly indicates that the areas where soybean is likely to be the most productive are directly associated with the Durban Metropolitan Open Space Scheme (shaded in green) creating a direct land use conflict.

SOURCE: Authors' own analysis.

and food security. Both tools consider climate impacts up to 2100, and the tool for London also incorporates socioeconomic projections in its analysis. Although both tools presented and visualized outputs in user friendly mapped form, the functionality, components and policy relevance of the two tools differ, primarily due to the availability of data and the motivations of the development teams. Both urban IA models provided insights into many different aspects of the relationship between global climate change and issues of adaptation and mitigation for their respective cities.

d. Stakeholder partnership

Stakeholder dialogue, drive and interaction were crucial in developing assessments in both Durban and London. The IA tool for Durban assessed and visualized a range of impacts of climate change, and was commissioned and managed by eThekwini Municipality (using local and internationally sourced funds) with local government officials and local decision makers as the intended end users. The technical work was

TABLE 1
Comparison of the assessment tools

	Tyndall Centre for Climate Change's Urban Integrated Assessment Facility (London)	eThekwini Municipality's Integrated Assessment Tool for Climate Change (Durban)
Key city pressures	* Developed large city in the global North * Population growth * Inequality * Development issues * Greenhouse gas emissions * Vulnerability to climate impacts: flood risk, water shortages, urban temperatures, air quality, windstorms, subsidence, ageing infrastructure	* Developing medium-sized coastal city in the global South * Poverty * Inequality * Underdevelopment * Loss of natural ecosystems * Vulnerability to climate impacts: vector-borne diseases, floods, droughts, storm surges, changing distribution of plant and animal species, infrastructure damage (human safety, insurance costs), lack of infrastructure, coastal erosion, food security, water availability, heat stress, energy consumption, negative impact on tourism
Model drivers of long-term change	* Socioeconomic change (demographic and economic scenarios used up to 2100) * Climate change (UKCP09 probabilistic scenarios used up to 2100)	* Climate change (downscaled data from School of Bio-resource Engineering and Environmental Hydrology (UKZN)) included projected changes in parameters for the medium (2045–2065) and long (2081–2100) terms for a wide variety of parameters, including temperature (mean annual and mean monthly), rainfall (mean annual and mean monthly), extreme events (with different return periods) and occurrence of droughts
Functionality of the tool	* Downscaling methodology for generating city-scale scenarios of urban economic indicators and land use * City-scale greenhouse gas emissions accounting tool * City-scale climate impact assessment * Evaluation of city-scale assessments, strategies and technologies for reducing impacts of climate change and greenhouse gas emissions	* Identifies critical geographic areas and sectors that are potentially at risk due to climate change * Facilitates an analysis of the possible inter-sectoral and cumulative impacts of climate change * Promotes an improved level of understanding of development implications through spatial representation of likely climate change impact * Enables city-scale greenhouse gas emissions scenario forecasting

Components of the tool	* Regional economic analysis
	* Land use change
	* Carbon dioxide emissions from energy usage and generation, personal transport and freight transport
	* Climate change impacts: flood risk, drought, urban heat
	* Exploration of individual and portfolios of adaptation and mitigation strategies
		* Climate modelling and downscaling
		* Prediction of climate change impacts in the following areas:
		  • human health
		  • agriculture assessment
		  • emissions accounting and forecasting
		  • plant species and vegetation type distribution
		  • extreme events – rainfall and stream flow
		  • sea level rise

Policy options analyzed	* Land use planning * Energy policy * Transport infrastructure and fuel efficiency * Water resource management * Flood risk management	* Not possible to use it for policy level analysis due to quality and scale of data available and difficulties in analyzing results of pair-wise comparison of sectoral layers; has a largely heuristic value in presenting scenario results and suggesting further investigations

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undertaken by a locally based consultancy firm, and municipal officials, councillors and local academics formed a project steering committee. This committee decided which sectors would be most significantly impacted by climate change and agreed which global emissions scenario best reflected Durban's development objectives. Municipal officials were also involved in reviewing the sectoral information included in the impact assessment section of the tool and articulating the level of functionality that would be required from the tool.

London's IA model was developed by an inter-disciplinary team of universities funded by a research grant working with, but not for, local government. Despite this, key stakeholders from the Greater London Authority, Transport for London, the Environment Agency (with responsibility for flood management), Thames Water (who provide drinking water to most of London) and academic mentors advised on relevant studies and tools, provided access to relevant datasets, identified policy questions that the research could address and identified policy options to be analyzed. Development of the London UIAF began with a series of meetings and interviews with these organizations in order to identify key policy questions and the extent to which they could be addressed by the research programme.

Keeping stakeholders engaged throughout the development process was challenging in both studies due to the long development time (three to four years). In both cases, the inter-disciplinary approach required a number of experts to work on different components, each embarking upon a steep learning curve to gain a full appreciation and understanding of the various assessment components before they could be coupled together and start to share datasets and results. Financial pressures required that, apart from a core team, many of the experts moved on to other projects following delivery of their component and before completion of the overall tool. In both London and Durban, this slow development frustrated some key stakeholders. This was exacerbated by long breaks between steering committee meetings, which were necessary to undertake the work and deal with the technical difficulties encountered in the development of the tool.

New questions did emerge in London as the policy agenda evolved (including a change of mayor), but also as insights from the modelling process emerged and as stakeholder understanding of what could be expected from the approach converged with that of the research team. The stakeholder team in London was perhaps more accustomed to the pace of research projects and, while many of the policy makers hoped for immediate answers to a number of questions, the steering committee remained supportive. At the outset, it was hoped that the UIAF could directly feed into London's strategic planning document, the London Plan,[39] which sets out a fully integrated economic, environmental, transport and social framework for development to 2031. The research was not completed in time to be included before the documents went for consultation. Through a Policy Placement Scheme, however, a researcher was placed at the Greater London Authority in order to use the UIAF to analyze some of the possible futures that were considered in the London Plan. The relationships built during the co-development of the UIAF have facilitated further joint research projects, and results from this and subsequent research projects will be considered when the next strategic plan for London is developed.

39. See reference 24.

e. Using information from integrated assessments

IA presents challenges in terms of institutional capacity to use the tools and enable participation of stakeholders in the decision-making process.[40] The complexity of such approaches, compared with available skills, is a major barrier to these models being incorporated fully into routine decision-making within local and national governments. The complexity of the processes being represented creates technical detail that is difficult for officers who typically only work with their own disciplines to understand. For example, given the technical sophistication of the London analysis, rather than deliver a model to end users, the research team worked interactively with stakeholders to identify and explore policy options, going through a modelling process and coupling with the other components of the assessment before presenting it back to the planners in the form of new quantified projections of the implications of alternative planning policies.

There was also very varied capacity among steering committee members in both cities to understand the purpose and limitations of the work. Spatial presentation of the data encouraged multi-stakeholder interaction and discussions around issues of climate change within the city administration predominantly, but also with some political and academic representatives. While both IA tools can perform pair-wise comparison of policy options, the Durban IA tool is heavily dependent on user knowledge and insight to interpret what the comparison might suggest, and is challenged by the variable accuracy and scale of the data sets used. As a result, the tool is only able to directly support a few city officials and consequently has not been widely used as had been hoped initially.

In addition, many climate response measures, for instance managed coastal retreat, will require public understanding and cooperation. Mitigation targets will only be achievable through public participation, for example using public transport instead of private cars. Scenarios can help demonstrate the impact of not taking action against the impacts of climate change, and the impact maps can aid decision makers and city dwellers who might be directly affected and who may also need to carry the burden of adaptation options financially through the raising of taxes, for example to provide investment for new infrastructure, where necessary. However, there is a disparity between the type and level of information required by most urban decision makers and the general public, which poses additional challenges for the communication of IA information.

Comparison of the two experiences highlights the difficulty of producing a tool that decision makers can readily use but that is still scientifically and technically valid. The Durban tool has turned out to be of more heuristic than analytical value, while the London tool has not yet made the transition from research to end user tool.

f. Model and data limitations

Both assessments represent substantial exercises in data-gathering, modelling and presentation of results. But did these technical outputs actually meet the needs of the policy makers? Different end users represent different sectors, with different problems and analysis needs.

In London, the UIAF considered the impacts of flood risk, water resources and urban heat. The flood risk module allows results to be

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presented on a 100-metre grid, which clearly shows the possible effects on buildings and land use at the level of detail required by decision makers. Similarly, results and findings from the water resources module are available in metrics familiar to the policy makers. The urban heat module provides information on the number of vulnerable people who could be exposed to heat waves, however outputs were only available on a five-kilometre grid. The issues being raised by policy makers concerning adaptation of buildings would have required additional simulation of urban climatology, which resources did not allow.

Technological challenges limited the utility of the Durban tool. Because the intention was to produce a tool that could be used by local decision makers, a stand-alone GIS platform was developed that did not require specialist GIS skills. Nevertheless, in order to accommodate representation of all the sectoral and climate datasets, the tool has become too technically difficult for most decision makers to navigate and is not sufficiently sophisticated to provide detailed design variables, for example for adaptation options. The analysis was further limited by the varying scale and quality of data available for the various sectors represented and the fact that much of the data could only be modelled coarsely at a macro level. Dependence on the knowledge of the user and the variable quality of the data presented means that interpretation of impact and identification of appropriate policy responses will vary greatly among users, with no objective way to adjudicate accuracy. Recent advances regarding crowd-sourced data from mobile phones and social networks,[41] coupled with open-source mapping and community mapping initiatives,[42] offer promise for future studies both here and in locations with even less data.[43]

A comparison of both tools highlights the need to consider the type of decisions an IA is being developed to inform. While spatial planners may only need macro-scale information on land use and flood extent to characterize vulnerability, urban drainage designers require data and findings at a much higher spatial resolution. Individual problem drains and gullies need to be identified and simulations driven by sub-hourly rainfall scenarios. Many other local government decisions are at the street or suburb level.

The promise of IA led to some high expectations among stakeholders in both cities. For example, in Durban the requirement from the planning sector that the IA tool provide a way of analyzing the implications of climate change for the spatial form and land uses proposed in the city's spatial development plans could not be met in any scientifically rigorous manner given the nature of the software package developed and the quality and resolution of the data available. It has subsequently been challenging to explain why the envisaged end product could not be delivered, creating frustration among the planning stakeholders who anticipated that a "solution" would emerge after the long and resource-intensive process. Ultimately, too much was expected of the Durban IA tool, and the technical, data and financial resources were too limited to fulfil those expectations.

g. Future directions

The long-term nature of urbanization processes means that, just like the climate system, decisions that are made now in cities could lock-in

41. Ratti, Carlo, Riccardo M Pulselli, Sarah Williams and Dennis Frenchman (2006), "Mobile landscapes: using location data from cell phones for urban analysis", *Environment and Planning B* Vol 33, No 5, pages 727–748; also Hughes, Amanda L and Leysia Palen (2009), "Twitter adoption and use in mass convergence and emergency events", *International Journal of Emergency Management* Vol 6, No 3–4, pages 248–260.

42. Berdou, Evangelia (2011), "Mediating voices and communicating realities. Using information crowd-sourcing tools, open data initiatives and digital media to support and protect the vulnerable and marginalized", Final Project Report, Institute of Development Studies, Brighton, UK, 32 pages; also Taylor, Anna, Sukaina Bharwani and Basra Ali (2010), "Enabling climate adaptation: from information to network-building and knowledge integration", in Hannah Reid, Saleemul Huq and Laurel Murray (editors), *Community Champions: Adapting to Climate Challenges*, IIED, London, pages 25–26.
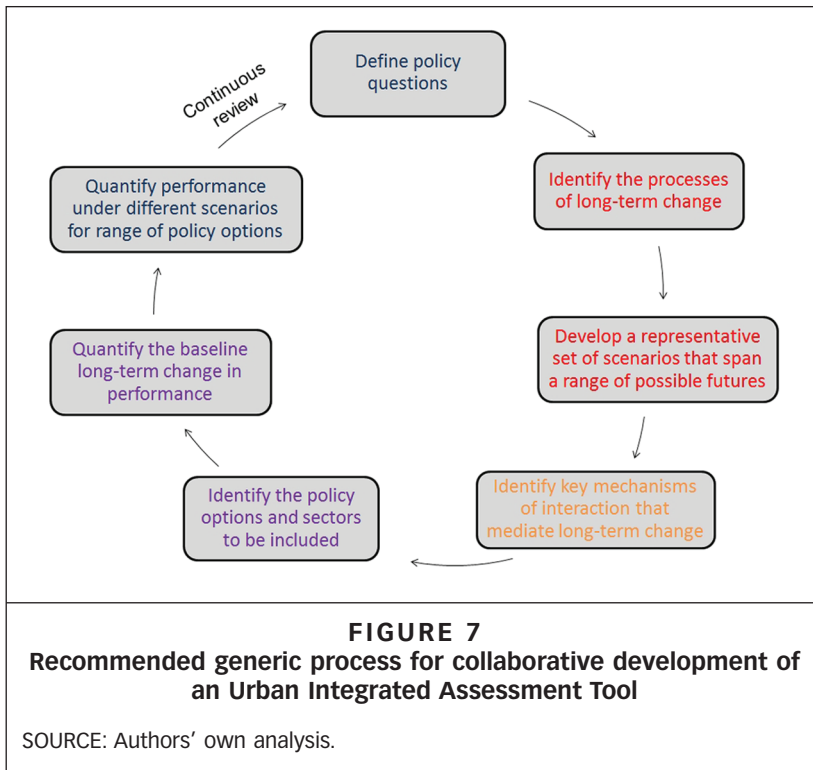
43. Livengood, Avery and Keya Kunte (2012), "Enabling participatory planning with GIS: a case study of settlement mapping in Cuttack, India", *Environment and Urbanization* Vol 24, No 1, April, pages 77–97.

development trajectories for a long time. If urban decision makers are to grapple with the complexities of global climate change, there is a clear need to translate the effect of changing macro-scale drivers at the local level. IA tools deal with these processes from an integrated systems perspective to provide internally consistent quantified scenarios of long-term change in urban areas. By modelling urban areas as systems, IA tools can begin to understand the synergies and conflicts between different policies and can begin to develop portfolios of measures that together have a realistic prospect of achieving sustainable outcomes. The number of urban processes and interactions that are incorporated in the analysis could be overwhelming. Until relatively recently, putting these insights together into an integrated assessment that helps to inform decision-making has defied researchers. There are technical reasons for this, but we also recognize the practical challenge of assimilating complex model-based evidence into decision-making processes, and there is still much to learn about how the sorts of evidence and insight from urban IA models could be used by decision makers. Yet doing so provides a great opportunity to understand better the potential direct and indirect consequences of decisions and to develop portfolios of measures that aim to address a number of different challenges in a synergistic way. Indeed, given the complexity of interactions and the large range of possible futures and decision options, it is hard to see how system-scale policy analysis of long-term change could be conducted without the support of computer-based tools.

IA modellers face a dilemma that they will only realistically be able to satisfy expectations of stakeholders – of which there are many in urban areas – if they have clearly defined policy questions that the IA is intended to inform. Yet paradoxically, we have identified that the benefit of the IA process is to help understand complex systems and frame policy questions. Thus, inevitably, the questions that the IA is seeking to inform will rarely be well defined from the outset.

The development of IA tools for London and Durban has been complex, challenging, resource intensive and time-consuming. The complexity and volume of processes that could be included means that an IA cannot provide all the answers or "design variables" that might be sought, but it does stimulate the conversations and interactions that are needed to drive forward climate adaptation and mitigation agendas. Such a common framework aids long-term understanding of the complexity of climate impacts and interactions across different sectors within a city, providing the context against which more detailed design can take place. A collective understanding can minimize contested planning decisions and help to identify synergetic rather than conflicting adaptation and mitigation measures and decisions.

Both of our studies approached urban systems from the point of view of climate change. Climate change is, of course, not the only long-term policy driver acting upon urban areas, so while we approached cities from this particular perspective we had to incorporate a range of other social, economic and environmental issues. Nonetheless, climate change has provided a particular lens through which to explore urban change and has distinguished these two assessments from alternative perspectives, which could include analysis from the point of view of urban and regional economics, transport and communications, urban resilience and disaster risk reduction. While the approach we have adopted has some

FIGURE 7
Recommended generic process for collaborative development of an Urban Integrated Assessment Tool

SOURCE: Authors' own analysis.

commonalities with each of these approaches, we have found that the lens of climate change adaptation and mitigation has helped to provide structure to what could be an overwhelmingly complex system (Figures 1 and 4).

We have been asked repeatedly about the transferability of the research to other cities. Many of the data used in both tools were from nationally collected sources (for example, census information), although not all of them were readily accessible through public bodies. From a technical point of view both tools are transferable, but the process of framing climate-related questions and understanding the relevant systems and interactions is an essential precursor to a quantified analysis, which will have to be re-worked for, and matched to the needs of, any given locality. More fundamental is the need to have decision-making processes in place that can assimilate the type of evidence that IAs provide. This can challenge qualitative approaches to planning decisions in urban areas but, on the other hand, it can also provide a new platform for collective learning and building consensus. On the basis of our experiences, we recommend that those planning urban IA tools place interaction and engagement between researchers and stakeholders at the centre of the process (Figure 7). From the outset, policy questions and drivers need to be defined by the end users in order to manage expectations and set a realistic scope for the IA. Not only does this give the research relevance in a policy context, it also gives the decision makers a sense of ownership and hence willingness to stay engaged in the process as it progresses,

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which is particularly important in an evolving policy landscape. Potential policy options at the city scale, i.e. those that are under the control of local decision makers, need to be identified. These can include mitigation and adaptation options that have already been implemented or suggested in city plans, or the assessment could test the possibility of techniques that may be new to that particular place. Typically, the processes of long-term change that drive the analysis at a broader scale will be the same for most cities, i.e. climate change, population growth and economic change. Appropriate scenarios can then be developed that are specifically designed for that city; however, it is important to acknowledge that urban policy develops in a national and international context, not in isolation. Considering change over such a long timeframe is fraught with uncertainty, so it is essential that the assessment is set within an appropriate uncertainty framework.

In terms of the sustainability and catalytic effect of both processes, as the development of the tool in London progressed more stakeholders became involved, different sectors started to identify datasets that could be useful to each other, and new research projects were spawned. For example, a direct follow-on from the project in London was a funded research contract, ARCADIA (Adaptation and Resilience in Cities: Analysis and Decision-making using Integrated Assessment), which with many of the original stakeholders is investigating the impacts of climate change upon the urban economy and land use.[44] In Durban, there has been no direct follow-on work as it was realized that further investment in the local level IA tool would not be productive – as the challenges and resource constraints for developing such a tool are too significant to be solved at this point. The need for such an integrated assessment approach, however, has not lessened and the potential of such a tool became better understood during the development of the Durban IA tool; in this regard, the municipality is now involved in the initiation of a national level programme funded in part by the national Department of Science and Technology to establish a South African Integrated Assessment Model (SA-IAM). The goal of this project:

> "… is to put in place, within three years, the tools to support an integrated planning approach in South Africa. Specifically, it aims to identify, acquire, develop and link the models needed to develop 10- to 50-year scenarios … This IA platform, which will be multi-institutional and have a variety of funding streams, will continue and evolve beyond the project period."[45]

The intention is to develop and link local IAs to the SA-IAM as part of this process. EThekwini Municipality has been invited to be a key stakeholder in the process, providing a local government perspective, and will share the lessons learned from the development of the Durban IA tool. It is fair to say that without the IA tool experience, eThekwini Municipality would not be sufficiently capacitated to participate meaningfully and effectively in such a national level process. This raises institutional questions about who should act as the lead agent in developing such IA programmes, as the resources and constraints of local government (especially in the global South) are likely to limit efficacy; and yet, if this process is driven by research institutes or national governments alone, local government uptake is likely to be equally limiting. Partnership projects are likely to offer the best way forward.

44. Crawford-Brown, Doug, Mark Sydall, Dabo Guan, Jun Li, K Jenkins, Jim W Hall, Rachel Beaven, Chris Thoung and Annela Anger-Kraavi (2013), "Vulnerability of London's economy to climate change: sensitivity to production loss", *Journal of Environmental Protection*, Vol 4, pages 548–563.

45. Scholes, Robert J and Marc Pienaar (2012), "Integrated assessment models for South Africa (SA-IAM)", Science Plan, February, Version 1.0, unpublished report, Natural Resources and the Environment CSIR, page 2.

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Urban IA will inevitably require a trade-off between cost (for example, of acquiring data, time for model development), scope (number of sectors and processes represented) and resolution (scale and level of detail of analysis).

III. CONCLUSIONS

Based on our collective experiences in London and Durban, we conclude with the following lessons and reflections:

- The process of constructing an integrated assessment stimulates researchers and stakeholders from varying backgrounds to think and engage differently and, more importantly, to jointly consider implementing measures to reduce the risks and impacts associated with climate change.
- Different end users and sectors have different needs. It is essential to have stakeholder involvement throughout the process in order to ensure that the data used are understood and that the technical outputs align with their needs and input.
- Integrated assessments of this type do not produce design outputs; rather, they aim to provide strategic information crucial to delivering climate-sensitive cities. It is important to manage stakeholder expectations and be clear about what can and cannot be delivered by integrated models.
- There can be institutional and individual barriers to the uptake of integrated models and their results – the complex and diverse issues being considered are challenging for an individual to present and interpret. Moreover, these issues must be considered across a number of groups and departments within any organization.
- IA frameworks need to be flexible in order to adapt, if possible, to changing policy requirements, but also to evolve as the levels of understanding of stakeholders and the development of applications progress.
- Integrated assessment can be time-consuming to produce. Maintaining stakeholder interest for such a long period is challenging when decision makers often require immediate results. A patient "stakeholder champion", who is committed to the IA and prepared to make the case for it in their organization, makes a huge contribution to ensuring applied impact of the IA.
- Understanding the relationships between different sectors and the "language" used can slow progress, but a shared vision and joint deliverables help to ensure integration.
- The resources required to produce and utilize IA tools will often exceed the capacities of local governments, particularly in the global South. This suggests that multiple spheres of government and other stakeholder groups (such as research organizations) will need to work together to access the required resources and skills, identify locally relevant needs and build the capacity to interpret and utilize the outputs.
- An iterative approach to the design, implementation and testing of the IA can improve its uptake, utility and flexibility. Although design of integrated assessment must consider local factors, we have identified some general steps that we believe are relevant to urban integrated assessments.

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Although integrated modelling requires a substantial effort and additional resources (compared to individual sectoral projects), it can add considerable value by enabling trade-offs and synergies between policies to be explored. Moreover, it helps bring stakeholders together to develop a common understanding of processes and consequences of long-term change. That collective understanding is essential to managing global environmental change rather than becoming its victims.

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