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Simulating the impact of urban development pathways on the local climate: A scenario-based analysis in the greater Dublin region, Ireland

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HIGHLIGHTS

- The impact of different future development pathways on local climate are simulated.
- Sprawling scenarios increased sensible/stored heat across 7.7–14.9% of the domain.
- Greening rooftops resulted in the lowering the impact on local scale climate.

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ABSTRACT

In this study, the impact of different urban development scenarios on neighbourhood climate are examined. The investigation considers the relative impact differing policy/planning choices will have on the local-scale climate across a city during a typical climatological year (TCY). The aim is to demonstrate a modelling approach which couples a climate-based land classification and simple urban climate model and how this can be used to examine the impact differing urban forms and design strategies have on neighbourhood scale partitioning of energy and resulting consequences. Utilising the Surface Urban Energy and Water Balance (SUEWS) model (Järvi et al., 2011) hourly fluxes of sensible, latent and stored heat are simulated for an entire year under four different urban development scenarios. The land cover scenarios are based on those obtained by the MOLAND model for 2026 (Brennan et al., 2009) in our case study city Dublin (Ireland). MOLAND LULC are translated into local climate zones (Stewart and Oke, 2012) for examination. Subsequently, the types of building forms, vegetation type and coverage are modified based on realistic examples currently found across Dublin city. Our results focused on 2 principle aspects: the seasonality of energy partitioning with respect to vegetation and average diurnal partitioning of energy. Our analysis illustrates that compact scenarios are suitable form of future urban development in terms of reducing the spatial impact on the existing surface energy budget in Dublin. Design interventions which maintain the level of vegetation at a ratio $\geq$ 9:16 to artificial surfaces reduces the impact.

1. Introduction

Globally, city planners face significant pressures to accommodate a rapidly growing urban population. In the past 60 years, the urban population has increased by 3.154 billion and more than 50% of the global population are now urban; by 2050, it is projected that this proportion will exceed 66% (UN, 2014). Urban areas are a focus of human activity, energy consumption and greenhouse gas emissions and consequently are major drivers of global climate change; moreover, their locations at low altitude, along rivers and close to coasts exposes them to hazards (such as coastal flooding) that are likely to be exacerbated in under various climate change scenarios (IPCC, 2014). Urban areas also modify the local climate profoundly, producing well known climatic phenomena such as the urban heat island (UHI) (Karl, Diaz, & Kukla, 1988; Patz, Campbell-Lendrum, Holloway, & Foley, 2005), CO_2 dome (Balling, Cerveny, & Idso, 2001; Idsoa, Idso, & Balling, 1998) and photochemical smog (Gray &

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Finster, 2000; Moussiopoulos, Sahm, & Kessler, 1995). These local to global climate effects are caused by two different, but related, aspects of cities. Urban form describes the surface cover (e.g. impervious fraction), the construction materials (e.g. asphalt) and the built geometry (e.g. the building dimensions and their juxtaposition). Urban function describes the activities in cities that require water, energy, materials etc.; the waste heat, vapour and materials are deposited into the atmosphere, hydrosphere and lithosphere. Urban form and function are strongly related so that, for example, more compact and densely occupied cities have lower per capita fuel use for transportation (Bramley & Power, 2009; Breheny, 1991; Elkin, McLaren, & Hillman, 1991; Mills, 2007).

As the world continues to urbanise, the global sustainable development challenges (and opportunities) will increasingly be concentrated in cities. Urban policies that address these must manage aspects of urban form and functions to mitigate (and adapt to) climate changes at different scales. This is especially true for economically developing countries where the rates of urbanisation are greatest and population growth outstrips the pace of planned development (Jorgenson & Rice, 2010; Martine, McGranahan, Montgomery, & Fernández-Castillia, 2008). The emerging layout of these fast-growing cities (e.g. urban extent, population and building density) will have long-term implications as once constructed, cities have proved difficult to alter. Incorporating climate knowledge into urban decision-making will be an important component in urban planning and creating more sustainable cities. In this respect, urban climate models (UCMs) are a potentially valuable tool for evaluating the impacts of different urban designs, land use, population densities and activities on the surface energy and water balances and the consequent effects on the local atmosphere and hydrology, respectively. Addressing local climate conditions (such as the UHI) can help reduce the contribution of individual cities to global climate change. In fact a variety of UCMs have been applied for precisely this purpose (see Table 1), yet there is little evidence that they have been used to inform spatial decision making (Eliasson, 2000; Hebbert & Mackillop, 2013; Mills, 2008; Oke, 1984). By comparison, climatic considerations are routinely employed to assist building design (Brager & de Dear, 1998; Givoni, 1992; Shaviv, 1984).

This ‘knowledge circulation failure’ (Hebbert & MacKillop, 2013) has been attributed to many causes, including a mismatch between urban climate knowledge and planning/design concerns. For example, while climate research has examined the nocturnal UHI in considerable detail, architects and planners are most interested in daytime conditions when people occupy outdoor spaces and building energy demands are highest (Svensson & Eliasson, 2002). To overcome this failure, existing research should be codified for planning use (Alcoforado, Andrade, Lopes, & Vasconcelos, 2009; Mills et al., 2010) but also new research needs to be undertaken that meets urban planning needs (Gál & Unger, 2009; Marland et al., 2003; Ward, 2003).

The use of land cover scenarios as one component of a planning support system is well established as a means of exploring factors which can be controlled by practitioners, and how they might be used to improve planning decisions and outcomes (Couclelis, 2005; Xiang & Clarke, 2003). They are valuable tools for exploring the spatial impact of decisions on future land cover (Van de Voorde et al., 2016) and for testing particular policy priorities on future land use and land cover change (Veldkamp & Fresco, 1997) or for exploring the impact of land cover on physical processes and risks, such as precipitation runoff (Niehoff, Fritsch, & Bronstert, 2002). In this respect, while a scenario should be viewed as a possibility or projection rather than as a prediction, scenario-sets can be extremely useful for examining bio-physical impacts of urbanisation, and thus help reduce any inadvertent consequences associated with urban development when combined UCMs which have been evaluated in many circumstances and have demonstrated their potential for planning applications (Grimmond et al., 2010, 2011).

Previous research has demonstrated how available meteorological data can be used to run mid-to-complex urban energy balance models, which would allow the urban climate effect to be included in the planning process (Alexander, Mills, & Fealy, 2015; Grimmond & Oke, 2002). However, there has been little guidance on how to run UCMs using inputs from land cover scenarios, interpret their findings and integrate their projections to inform policy.

In this study, we demonstrate the utility of the surface urban energy and water balance scheme (SUEWS v.2013b) for evaluating the climatic impact of different scenarios of urban development. SUEWS is parameterised using values obtained from the Local Climate Zone (LCZ) scheme that describes neighbourhood types and is run using available meteorological data. This approach is applied to a case study city (Dublin, Ireland, 53.3° N, 6.3° W) where the pathways for future growth are based on scenarios generated by the MOLAND model to 2026. These scenarios generate distinct land use and land cover (LULC) outcomes, which are translated into LCZ types to provide required parameter values. The output of the model illustrates the impacts of the different development pathways. Before discussing the methodology in detail, the potential value of the SUEWS model – linked with the LCZ scheme – for planning purposes is presented.

2. Integrating LCZ and SUEWS to support planning decisions

The LCZ scheme categorises landscapes into types based on their impact on the near-surface air temperature (Stewart & Oke, 2012); it consists of 17 standard types, 10 of which are urban, 7 are non-urban (Fig. 1) but it can also accommodate mixed types. The scheme is properly applied at the local or neighbourhood-scale (areas greater than about 1 km^2) where each type is differentiated from another based on a range of variables, such as, the fractional impervious cover, mean building height, building materials, sky view factor and anthropogenic heat generation. The net effect of these properties is to modulate the thermal response of the overlying atmosphere and create the urban heat island (UHI) phenomenon; this link has been validated in published work (Levlovics, Gál, & Unger, 2013; Stewart, Oke, & Krayenhoff, 2014). The value of the LCZ scheme extends beyond the UHI however, and could provide a platform for incorporating much urban climate knowledge into planning practice for a number of reasons:

- First, the UHI may be regarded as an indicator of urban climate effects generally, so mitigating it addresses other effects such as the lack of greenspaces and of available water. So a map of LCZ types in a city identifies where the urban effect is greatest.
- Second, LCZ types are designed to be culturally neutral (applicable internationally) and intuitive (user-friendly). As such they can clarify communication between climate scientists and planners e.g. Picone & Campo (2015) see Fig. 2. Moreover, they can facilitate knowledge transfer between cities.
- Third, LCZs are useful for both observational and modelling studies of the local scale climate. A LCZ map of a city can be used to sample the urban landscape to measure climate variables and to gather more detailed information on surface characteristics to run UCMs. Even the current variables in the LCZ scheme correspond with the many UCM parameters.

Here, we link the LCZ scheme with the SUEWS climate model v.2013b (Järvi, Grimmond, & Christen, 2011) to explore the impacts of urban development scenarios on neighbourhood scale climate. By integrating LCZ with SUEWS, urban form is accounted as either