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413: Modeling the impact of future development pathways in a mid-latitude city on the urban energy balance

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1. Introduction

Like many European cities, Dublin (Ireland) has seen a decline in development for the past number of years owning to suppressed economic activities. However as documented in national and international news, there is now a significant housing crisis in Dublin as economic recovery begins to take hold and concentrate in the city. This has led to high demand for both housing and office space with virtually no new supply in the past 7 years. In turn, there is increased pressure for the Dublin local authorities to begin development of new residential and commercial units to ease the rising demand. In response to this unprecedented situation the government of Ireland recently announced an emergency €1.5 billion investment in direct provision for some 35,000 additional social housing and commercial units with development to begin as early as 2016. In some respects, this is analogous (though notably less extreme) to the situation in urban areas in developing economies where the pace of inward migration outstrips the pace of planned development (Jorgenson & Rice, 2010). Hence, integrated policies aimed at improving the lives of both urban and rural dwellers are urgently needed.

Integrating climatic considerations into building and neighbourhood design has a comparatively longer history than the use of specific urban climate knowledge during the planning process (Brager & de Dear, 1998). As a result, there is an apparent mismatch between the level of urban climate knowledge, which is now well established and of a high standard, and its integration into the planning process, which is rare and unsystematic (Oke, 1984; Eliasson, 2000). In some instances where no previous research in an urban area exists, planners have utilised standard meteorological data from outside the urban area to compensate for this knowledge gap, which appears reasonable in the first instance since the inclusion of some local climate knowledge seems better than none. However the fact remains the use of these kinds of climate data are ultimately inappropriate for accounting for urban climate effects in the planning process, since meteorological stations located outside the urban domain are not representative of urban climate effects (Lowry, 1977). In fact, most meteorological stations conforming to WMO standards seek to deliberately avoid the urban climate effect from contaminating observations (Oke, 2006). However, previous research has demonstrated how these data can be utilised to force a mid-to-complex urban energy balance model, the results of which can be extended into the urban area, thus enabling the potential to include the urban effect in the planning process without the need for sophisticated urban meteorological observation (i.e. eddy covariance) platforms (Grimmond & Oke, 2002; Alexander et al., 2015). Achieving an urban form that reduces the impact of urbanisation on the population vis-à-vis local climate requires consideration of the interaction between the land surface and near surface atmosphere. In this respect, urban climate models (UCMs) are an invaluable tool for forecasting the impact of different urban forms, land use, population densities and activities on the surface energy and water balances, making them quite useful for planning purposes.

Urban development is known to impact on the local to regional scale climate, producing well known climatic phenomenon such as the urban heat island (UHI), CO_2 dome and photochemical smog. Reducing the impacts of these phenomenon on the urban population is a significant challenge, but it has long been recognised sustainable solutions can be realised by modifying the urban form (Mills, 2007).

Here, we undertake to simulate the impact each individual development pathway will have the on the urban surface energy and water balance of Dublin city. We employ the Surface Urban Energy and Water Balance Scheme (SUEWS) model (Järvi et al., 2011) to carry out our assessment of the impact on the urban energy (UEB) and balance. Our investigation considers the relative impact differing policy / planning choices will have on the local-scale climate during a typical meteorological year (TMY). We then developed Local Climate Zone maps for present day Dublin and for each development pathway scenario (2026) and, using this for land cover, model the diurnal, seasonal and annual energy and water budget for Dublin for each development scenario. Subsequently we provide an assessment of the each development path on the UEB.

2. Methods

2.1. Study Area

Our study area is the Greater Dublin Region (GDR) which covers Dublin city and parts of the surrounding counties containing several large satellite towns. The city is located on the east coast and is flanked by the Irish Sea to the East, and the Dublin/Wicklow mountains to the South. With the exception of the mountainous southern part, most of the city occupies a flat and low-lowing basin (<100 meters above sea level.) and is bisected by the Liffey River – figure 1 left. Given its latitude, it has a mild climate with little temperature variation through the year (Köppen type *Cfb*) although day-length is significant longer in summer (16 h in June) than in winter (8 h in December). The extent of the urban area under investigation extends to ~700 km^2 as the city has expanded outside its administrative boundaries over the last three decades. The population of the defined model extent is ~ 1.4 million. It provides an ideal place for this study as it has two flux observation sites (located in urban and suburban neighbourhoods) where detailed energy flux and meteorological observations have been made since 2009 (Keogh et al., 2012; Alexander et al., 2015). In addition there is a Local Climate Zone (LCZ – see Stewart & Oke (2012) for details) description of the city that outlines major neighbourhood types (Alexander & Mills, 2014) and a WMO standard weather station. These data allow SUEWS to be parameterized and run.

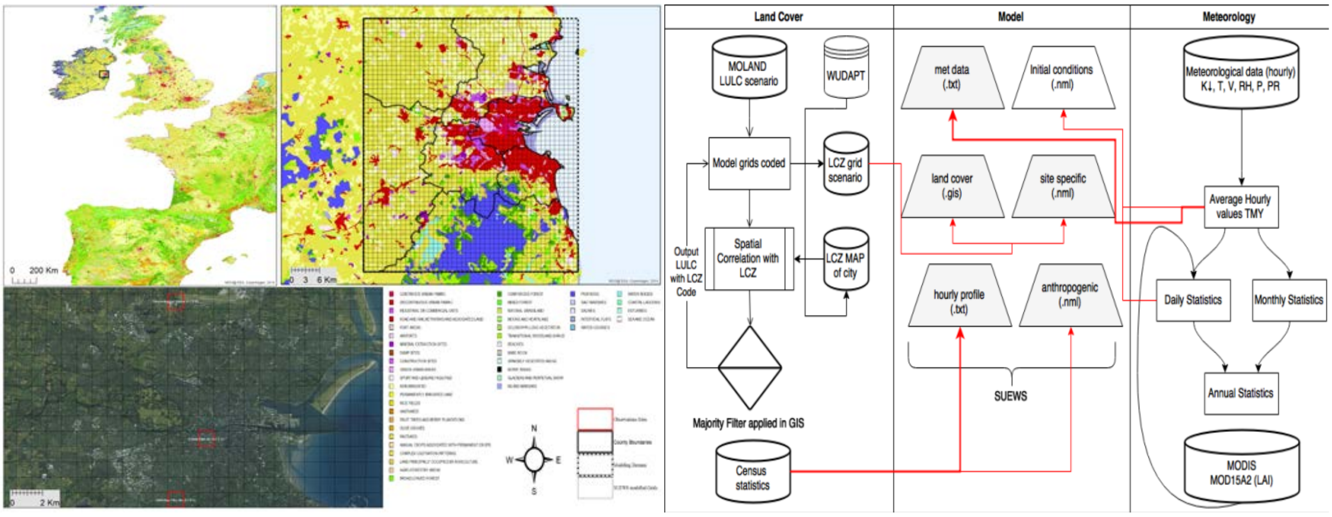

Figure 1: (Left) Study area overview and modeling domain. Images on top show CORINE land cover (2006) for Dublin city. Image below shows Google Earth satellite imagery. Red boxes illustrate grids containing observation platforms. (Right) Overview of datasets utilised for study separated into land cover / demographic (column 1) and meteorological / phenological (column 3) and how they are incorporated into the model (column 2)

2.2 Data

SUEWS requires hourly meteorological data, land cover parameters and estimates of anthropogenic fluxes. In terms of land cover, the model describes different surface types in a neighbourhood in terms of fractional coverage (λ) of buildings, pavements, water, vegetated areas (both irrigated and non-irrigated) and trees (coniferous and deciduous) and unmanaged land cover such as bare soils or rock. Anthropogenic water and energy use can also be provided; hourly water use can be expressed as a proportion of the daily total and hourly anthropogenic heat fluxes can be estimated from typical daily patterns, divided into weekday and weekend values. Figure 1 (right) summarises the input data used for this study.

The land cover data used here are based MOLAND scenarios for Dublin up to 2026 (see Brennan et al., (2009) and Williams et al., (2012) for further details). Rather than provide an overview of the MOLAND cellular automata model which is discussed in detail elsewhere (Barredo et al., 2003), a summary of the scenarios utilised in this study and how these were converted into land cover parameters required by SUEWS are given below.

In total five LULC scenarios were examined, present day land cover (hereafter referred to as the baseline case or BLC) and future development pathway (DP) scenarios for 2026 which are differentiated by different policy priorities. The policies informing the future scenarios can be divided into two broad categories; 1) those based on current regional planning guidelines which emphasises strategic green belts between the Dublin metropolitan area and surrounding satellite towns, we refer to this development pathway as urban-densification 2) consolidation of the metropolitan footprint (MF) with surrounding urban areas by expansion along transport corridors, we refer to this development pathway as urban-expansion (sprawl). The four DPs are summarised below:

(i) DP-1; Business as usual development based on recent trends
(ii) DP-2; Urban-Expansion along transport corridors
(iii) DP-3; Urban-Consolidation with strategic satellite towns
(iv) DP-4; Urban-Densification of existing MF and satellite towns

In order to translate the different land cover classes utilised in the scenarios to a format usable by SUEWS (fractional coverages of buildings / pavements / vegetation / trees / water / unmanaged soils) we took the following approach. Firstly, the MOLAND land-use land-cover (LULC) classes were spatially correlated with a pre-existing LCZ dataset for Dublin – Table 1.

Table 1: MOLAND LULC classes converted into corresponding Local climate zones (LCZ) in the study area, the parenthesis in the LCZ column contains the number of grids (n) that are coded to that LCZ class for the BLC. Plan area fractions (λ) were obtained from Alexander et al. (2015). Population are given as persons per km^2, the values in parenthesis in this column represent population in 2026.

MOLAND LULC	LCZ Name **"Code"**	Built	Impervious	Unmanaged	Trees	Grass	Water	Population
Urban LCZ (n=342)								
Residential continuous medium dense urban fabric; Commercial areas; Public and private services	2 Compact Midrise **"LCZ 2"** (12)	33	55	00	06	06	00	10130.2 (11981.0)
Residential continuous dense urban fabric	3 Compact Lowrise **"LCZ 3"** (1)	22	61	00	07	10	00	3867.6 (4574.2)
Port areas; Roads and rail networks and associated lands	5 Open Midrise **"LCZ 5"** (1)	13	48	00	11	28	00	2335.2 (2761.8)
Residential discontinuous urban fabric; Residential discontinuous sparse urban fabric	6 Open Lowrise **"LCZ 6"** (270)	14	52	00	11	23	00	3887.9 (4598.2)
Industrial areas; Construction sites; Airports; Mineral extraction sites	8 Large Lowrise **"LCZ 8"** (58)	30	61	00	04	05	00	1380.7 (1633.0)
Non Urban LCZ (n=2142)								
Forests; Semi-natural areas	A Dense Trees **"LCZ 101"** (104)	01	02	04	48	45	00	48.3 (57.1)
Arable land; Pastures; Hetrogeneous agricultural areas; Dump sites; Artificial non-agricultural vegetated areas; Restricted access areas	D Low Plant **"LCZ 104"** (1492)	03	08	03	18	67	00	185.5 (219.4)
Wetlands	F Bare Soil/Sand **"LCZ 105"** (245)	06	20	55	19	00	00	0.0
Water bodies	G Water **"LCZ 107"** (301)	00	00	00	00	00	100	0.0

SUEWS is capable of simulating local scale anthropogenic heat flux (Q_F) utilising specified population density per grid, daily mean Q_F which is adjusted based on a diurnal energy use profile. The population density per grid were obtained from the national census of Ireland (C.S.O., 2012). Population density extrapolated for 2026 were based on the population growth trends from previous census statistics – see Table 1. For the model simulations, weekday and weekends are differentiate with two separate hourly Q_F profiles. Q_F was set to be slightly lower in summer months (May-September) than the winter months to reflect reduced space heating demand, as would be expected for a middle-latitude city (Offerle et al., 2005). For example, for LCZ 2, December Q_F was 44.3 W m^{-2} whereas July was set to 34.0 W m^{-2}.

Finally, we obtained hourly values for T, RH, Pr, P, V and K↓ for the past 10 years from a meteorological station located close to Dublin airport approximately 5 km north of the inner city. We averaged the hourly values for each day of the year in order to derive a typical meteorological year (TMY). The resulting hourly dataset was used to force the model in each of the four MOLAND scenario runs and an additional run for the BLC to examine the impact on the UEB.

3. Results

3.1 Annual and seasonal flux variation

The annual magnitude of Q_H for LCZ 2 was 59.2 W m^{-2} compared to 47.0 and 39.8 W m^{-2} for LCZ 6 and LCZ D respectively. Mean ΔQ_S for non-urban LCZ was slightly negative when taking the entire year (and all hours) into account, meaning these surfaces lost slightly more energy than they gained in terms of storage. LCZ 2 had an annual value of 21.2 W m^{-2} which was higher than the most abundant non-urban LCZ class (LCZ D) value, -10.1 W m^{-2}. ΔQ_S for LCZ 6, which is spatially related to residential areas, had an annual magnitude of just 1.2 W m^{-2}. This LCZ relationship relates to the nocturnal urban heat island, leading to warmer air temperatures in compact areas of the city compared to vegetated areas and has been demonstrated previously. The differences in the annual mean values for Q_H and Q_E in each LCZ type are illustrated in Figure 2a. In all DP scenarios, the presence of water and vegetated LCZ can be seen to reduce the annual magnitude of Q_H and increase the annual magnitude of Q_E.

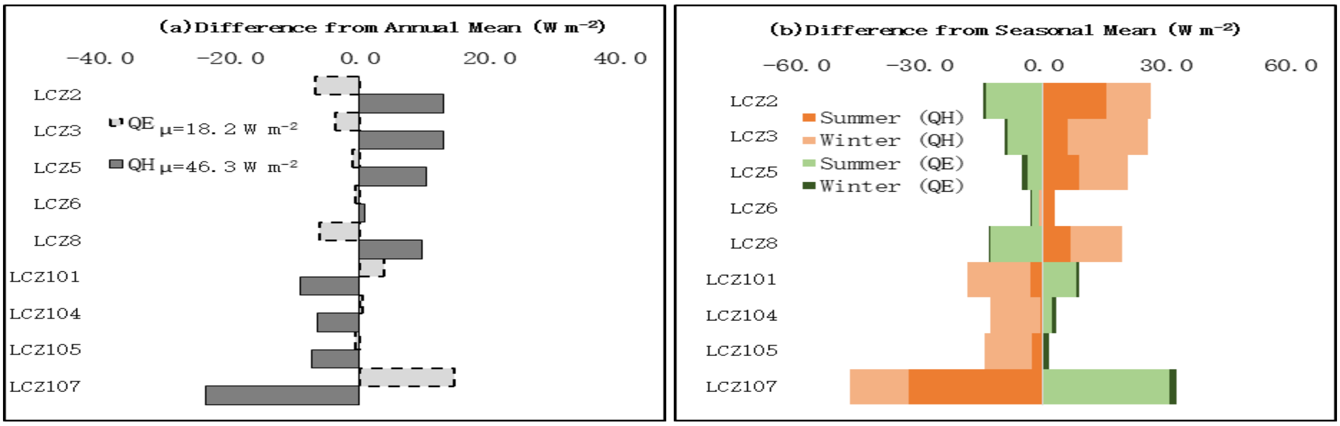

Figure 2: (a) Difference from annual mean Q_H and Q_E, this is the mean value taken across all LCZ types, positive values indicate above average annual flux magnitude, negative values indicate below average annual flux magnitude. (b) Differences as with (a) however the values are further divided into sesaonal Q_H (orange shades) and Q_E (green shades).

The annual and seasonal differences in energy partitioning between LCZ when $Q^* \geq 0$ W m^{-2} are summarised in Table 2. Generally the ratio of turbulent fluxes to available energy (i.e. χ: Q_H/Q^*, γ: Q_E/Q^*, Λ: $\Delta Q_S/Q^*$, β: Q_H/Q_E) follows previous work (Grimmond & Oke, 1995; Keogh et al., 2012). For urban LCZ, the available energy was predominantly channelled into sensible heating and heat storage (annual χ = 56-68%, γ = 11-19% and Λ = 24-50%) whereas for the non-urban LCZ a higher fraction of the available energy was partitioned into Q_E (annual χ = 24-50%, γ = 20-34% and Λ = 16-26%).

Table 2: Proportioning of Q (χ, γ, Λ) and the Bowen ratio (β) when Q* ≥ 0 W m-2. Presented are unit-less flux ratios for annual and seasonal partitioning*

	χ (Q_H/Q^*)			γ (Q_E/Q^*)			Λ ($\Delta Q_S/Q^*$)			β (Q_H/Q_E)		
LCZ Code	**Ann**	**Sum**	**Win**	**Ann**	**Sum**	**Win**	**Ann**	**Sum**	**Win**	**Ann**	**Sum**	**Win**
LCZ2	0.675	0.572	1.024	0.115	0.103	0.178	0.507	0.465	0.634	5.884	5.541	5.764
LCZ3	0.568	0.449	0.953	0.139	0.133	0.195	0.323	0.397	0.042	4.098	3.368	4.882
LCZ5	0.591	0.499	0.896	0.168	0.166	0.215	0.265	0.346	-0.038	3.522	3.001	4.160
LCZ6	0.573	0.507	0.771	0.192	0.196	0.227	0.330	0.357	0.226	2.976	2.586	3.401
LCZ8	0.563	0.468	0.873	0.115	0.107	0.171	0.236	0.332	-0.115	4.901	4.387	5.102
LCZ101	0.515	0.504	0.512	0.268	0.282	0.255	0.158	0.211	-0.033	1.921	1.787	2.005
LCZ104	0.544	0.519	0.593	0.228	0.239	0.236	0.187	0.237	0.014	2.383	2.176	2.515
LCZ105	0.516	0.489	0.573	0.205	0.216	0.213	0.223	0.277	0.036	2.513	2.262	2.688
LCZ107	0.241	0.214	0.308	0.339	0.396	0.249	0.264	0.338	0.002	0.713	0.541	1.239

3.2 Spatial variation

To assess the impact relative to the BLC differences on a grid-by-grid basis were calculated by subtracting the annual mean of the BLC from each of the DPs. To examine significant spatial clustering of differences from the BLC, Getis-Ord G_i^* (Getis & Ord., 1992) was employed which compares local averages to the global averages. In this case, G_i^* illustrates where there are spatial clustering of increases and decreases in the turbulent fluxes relative to the BLC – see Figure 3.

As expected, the sprawling scenarios (DP2 and DP3) exhibited the largest spatial increase (that is, the number of areas with higher annual values compared to the BLC) in Q_H and ΔQ_S coupled with the largest decrease in Q_E (see Table 3). Taking the number of areas with increased Q_H relative to the BLC; DP3 exhibited the largest spatial increase in Q_H (14.1%) followed by DP2 (13.3%) DP1 (9.9%) and finally DP4 (6.4%). When the number of grids with decreases relative to the BLC were also taken into account, the ranking remained the same. The ranking for the number of areas with decreases in Q_E were similar, however the number of areas in DP2 relative to the BLC was marginally higher than DP3 (6.9% and 6.3% respectively). Q_E decreases were greater in DP1 than DP4. For ΔQ_S, the ranking was DP2 (15.6%) followed closely by DP3 (15.5%) then DP1 (9%) and DP4 (6.4%). Out of the four scenarios DP4 had the least impact in respect to Q_H, Q_E and ΔQ_S.

Table 3: The number of areas (as % of total model domain) with higher/lower annual values of Q_H, Q_E and ΔQ_S compared to the BLC

	Net spatial increase/decrease compared to BLC	Significance level					
Development Pathway	**(Σ Increase − Decrease)**	**+99%**	**+95%**	**+90%**	**-90%**	**-95%**	**-99%**
DP1							
Q_H	8.9%	4.8%	4.9%	0.2%	0.0%	0.0%	1.0%
Q_E	-2.2%	1.3%	0.3%	0.7%	0.9%	1.7%	1.9%
ΔQ_S	7.7%	7.9%	0.4%	0.7%	0.8%	0.1%	0.4%
DP2							
Q_H	12.1%	7.8%	3.4%	2.1%	0.0%	0.1%	1.1%
Q_E	-4.4%	1.5%	0.3%	0.7%	2.0%	2.4%	2.5%
ΔQ_S	14.9%	9.2%	2.1%	4.3%	0.1%	0.5%	0.1%

Table 3 continued									
DP3									
	Q_H	12.9%	8.5%	2.7%	2.9%	0.0%	0.0%	1.2%
	Q_E	-4.0%	1.4%	0.3%	0.6%	0.8%	2.5%	3.0%
	ΔQ_S	14.9%	9.0%	2.8%	3.7%	0.5%	0.1%	0.0%
DP4									
	Q_H	0.1%	6.1%	0.1%	0.2%	3.1%	0.5%	2.7%
	Q_E	0.0%	1.9%	0.3%	1.2%	0.2%	1.1%	2.1%
	ΔQ_S	0.7%	5.6%	0.4%	0.4%	2.9%	0.2%	2.6%

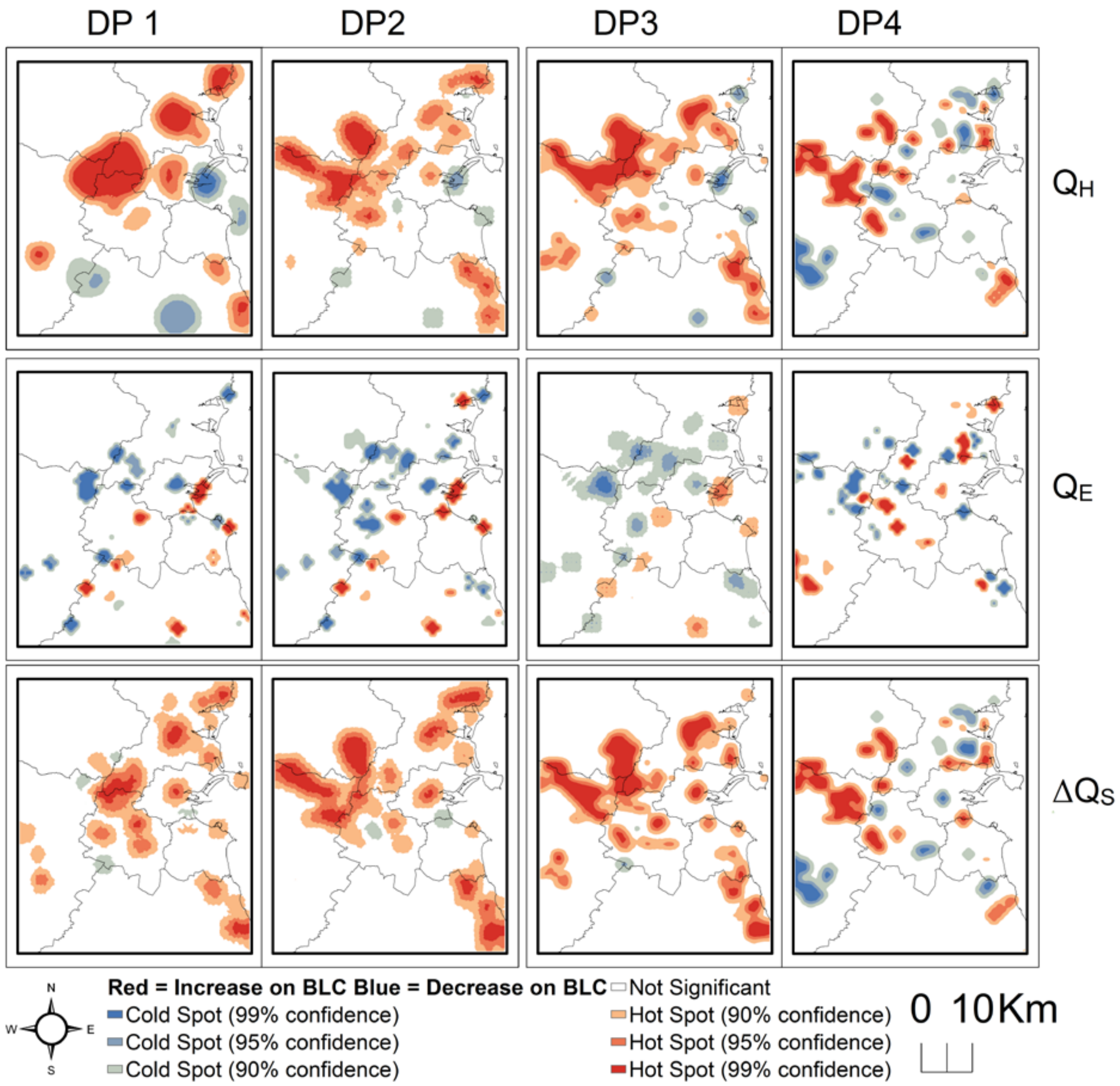

Figure 3: Spatial distribution of increases/decreases in turbulent fluxes (rows) compared to BLC for each DP (columns). The differences are based on annual mean values in W m^{-2}

4. Discussion and Conclusions

The impact of urban form and development on the urban energy budget (UEB) was examined under 4 distinct development scenarios in order to examine the optimum development pathway for Dublin city. The UEB was examined in terms of spatial changes due to urbanisation (primarily on the existing urban fringes), the seasonal differences in sensible, latent and stored heat in different areas. Employing the local climate zone (LCZ) scheme allowed for this examination and provides useful guidance (Stewart & Oke, 2012). However as with most urban areas, individual areas though similar in form and function will differ (i.e. intra-LCZ differences) somewhat in terms of specific fractional coverages of vegetation, buildings and pavements.

The use of very high resolution data, for example individual building footprints, heights, trees derived from a LIDAR system, would have allowed for examination of the UEB in greater detail and address the limitation of treating all LCZ areas equally. However, in data starved settings for example, cities in the economically developing countries, such an approach is not feasible, therefore this approach was not employed here. Moreover, there has been a recent call for standardisation in how urban areas are described in order to allow for more robust inter-city comparisons with respect to climate, impacts on human comfort, pollution and urban development (Ching, 2013; Bechtel et al., 2015).

While the replacement of natural, vegetated landscapes with artificial materials associated with urban areas will inevitably impact upon the surface energy budget the results here illustrate the type of urban development plays a significant role on this impact at the local scale, moreover seasonal considerations should be taken into account. The densification (i.e. upward development) of existing urban plots was shown to increase winter time ΔQ_S thus reducing the level of temperature changes within these areas (sensible heat). This will lead to increased levels of heat released back into the atmosphere at night, which serves to enhance the urban heat island effect under the right synoptic conditions. During the summer months, daytime Q_H increased in these areas due to multiple reflectance (i.e. increased Q*) which has major implications for daytime cooling requirements and human thermal comfort. Urban sprawl was shown to increase Q_H and ΔQ_S significantly in both winter and summer, and decrease Q_E in summer months. Again this has implications for energy use and human comfort thus strengthens the case for including such information in planning decisions.

Drawing from the results of this study, we conclude that the optimum development scenario is one which preserves a higher overall proportion of vegetated land cover (DP-4). Such development inevitably leads to an increased proportion of energy channelled into sensible heating of the near surface atmosphere and additionally heat storage within the urban fabric across the domain. Therefore design interventions which aim to reduce this impact locally should be further investigate. An effective solution maybe the inclusion of vegetation that is photosynthetically active throughout the summer months and remains active during the winter months which would serve to promote energy uptake by vegetation and thus increase latent heating.

We conclude that incorporating urban climate data into development and design processes where meteorological observations are otherwise absent is possible and allows for a range of development pathways and local scale impacts to be examined. Such applications serve to increase the incorporation of urban climate knowledge into the planning and design process which can ameliorate environmental conditions for the urban population and reduce the negative impacts of development.

References

Alexander, P.J. & Mills, G.M., 2014. Local Climate Classification and Dublin's Urban Heat Island. *Atmoshere*, 5(4), pp.755-74.

Alexander, P.J., Mills, G.M. & Fealy, R.J., 2015. Using LCZ data to run an Urban Energy Balance Model. *Urban Climate*, 13(3), pp.14-37.

Barredo, J.I., Kasanko, M..M.N. & Lavalle, C., 2003. Modelling dynamic spatial processes: simulation of future scenarios through cellular automata. *Landscape and Urban Planning*, 6(3), pp.145-60.

Bechtel, B. et al., 2015. Mapping Local Climate Zones for a Worldwide Database of the Form and Function of Cities. *ISPRS Int. J. Geo-Inf*, 4(1), pp.199-219.

Brager, G.S. & de Dear, R.J., 1998. Thermal adaptation in the built environment: a literature review. *Energy and Buildings*, 27(1), pp.83-96.

Brennan, M. et al., 2009. Regional planning guideline review : using MOLAND as part. *Urban Institute Ireland Working Papers Series; 09/07*, pp.1-23. Available at http://www.uep.ie/pdfs/WP%200907%20W.pdf .

C.S.O., 2012. *Census of Ireland 2011*. Available online: http://www.cso.ie/en/census/ (accessed on 18 April 2015). Dublin: CSO Central Statistics Office of Ireland.

Ching, J.K.S., 2013. A perspective on urban canopy layer modeling for weather, climate and air quality applications. *Urban Climate*, 3(1), pp.13-39.

Eliasson, I., 2000. The use of climate knowledge in urban planning. *Landscape and Urban Planning*, 48(1-2), pp.31-44.

Getis, A. & Ord., J.K., 1992. The Analysis of Spatial Association by Use of Distance Statistics. *Geographical Analysis*, 24(3), pp.189-206.

Grimmond, C.S.B. & Oke, T.R., 1995. Comparison of Heat Fluxes from Summertime Observations in the Suburbs of Four North American Cities. *Journal of Applied Meteorology*, 34(4), pp.873-89.

Grimmond, C.S.B. & Oke, T.R., 2002. Turbulent Heat Fluxes in Urban Areas: Observations and a Local-Scale Urban Meteorological Parameterization Scheme (LUMPS). *Journal of Applied Meteorology*, 41(7), pp.792-810.

Järvi, L., Grimmond, C.S.B. & Christen, A., 2011. The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver. *Journal of Hydrology*, 411(3-4), pp.219-37.

Jorgenson, A.K. & Rice, J., 2010. Urban Slum Growth and Human Health: A Panel Study of Infant and Child Mortality in Less-Developed Countries, 1990–2005. *Journal of Poverty*, 14(4), pp.382-402.

Keogh, S., Mills, G.M. & Fealy, R.J., 2012. The energy budget of the urban surface: two locations in Dublin. *Irish Geography*, 4(1), pp.1-23.

Lowry, W.P., 1977. Empirical Estimation of Urban Effects on Climate: A Problem Analysis. *Journal of Applied Meteorology*, 16(2), pp.129-35.

Mills, G.M., 2007. Cities as agents of global change. *International Journal of Climatology*, 27(14), pp.1849-57.

Offerle, B., Grimmond, C.S.B. & Fortuniak, K., 2005. Heat storage and anthropogenic heat flux in relation to the energy balance of a central European city centre. *International Journal of Climatology*, 25(10), pp.1405-19.

Oke, T.R., 1984. Towards a prescription for the greater use of climatic principles in settlement planning. *Energy and Buildings*, 7(1), pp.1-10.

Oke, T.R., 2006. *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites*. Geneva: WMO/TD. No. 1250. World Meteorological Organization IOM Report No. 81.

Stewart, I.D. & Oke, T.R., 2012. Local climate zones for urban temperatures. *Bulletin of the American Meteorological Society*, pp.1879 - 1900.