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RECYCL-3431; No. of Pages 14
ARTICLE IN PRESS
Resources, Conservation and Recycling xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

An urban climate assessment and management tool for combined heat and air quality judgements at neighbourhood scales

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ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form 18 June 2016
Accepted 7 December 2016
Available online xxx

Keywords:
Urban heat island
Air quality
Mortality
Weather research and forecasting model
Urban climate index
Health

ABSTRACT

Meteorology and air quality are key aspects for city life and urban metabolism. Both aspects build upon urban and natural processes, involve stocks and flows of heat and pollution, with in the end consequences for stocks and flows concerning other urban entities and processes such as human outdoor activities, leisure, transport modes, as well as for urban design and planning. During hot summer days cities experience an urban heat island effect mainly at the start of the evening and at night. As a result inhabitants might be subject to a reduced human thermal comfort. Hot summer days often also coincide with relatively poor air quality conditions. Both short-term effects are known to increase the mortality rates, and it is challenging to distinguish their impacts on health effects. Moreover, climate change scenarios indicate an enhancement of future heat wave frequency and intensity and a further deterioration of human thermal comfort. These issues raise the need and the urgency for city adaptation, but an integrated method for the assessment is still missing. Effective city adaptation is hampered by the complexity of the urban climate (induced by both meteorology and urban morphological characteristics) and its potential health risks, combined with the complex spatial interaction of stakeholders and economical functions. To warn the general public, and to effectively perform urban planning interventions, straightforward environmental indicators are required. Indicators have been developed for the individual aspects before, but indices that combine both air quality and urban heat are rather scarce (Rainham and Smoyer-Tomic, 2003). This study develops a novel metric that combines the impact of thermal comfort and air quality by accounting for the relative health risk for both aspects. A straightforward quantification method for this metric has been developed to provide an objective, rational assessment. The application of this new Urban Climate assessment tool is then applied to a case study for a heat wave in the Northwestern Europe, and applied for a sample intervention in the city center of Ghent (Belgium).

1. Introduction

Urban areas are sophisticated entities characterised by both a complex physical environment containing a variety of urban morphology and urban fabric, as well as a social environment where citizens live, work, travel and recreate. In order to understand urban developments at different spatial and temporal scales, both natural and man-made contributions to the urban systems and their interactions should be analysed. The urban metabolism model facilitates the description and analysis of the flows of the materials and energy within cities. It is a figurative framework to study the interactions of natural and human systems. For example Dijst (2013) presents a flow perspective on urban and natural systems, covering stocks and flows of both natural and anthropogenic origin. In such perspective, urban processes of varying temporal scales, such as land use design, population, housing, employment and travel, can be linked to natural processes. As an example on how these natural processes interact with urban traffic flows, Böcker and Thorsson (2014) studied the role of weather effects on cycling frequencies, cycling durations, and the exchange between cycling and other transport modes. They report negative effects of precipitation and wind speed, and a nonlinear bell-shaped relation between thermodynamic variables on cycling and opposite effects on car usage. In addition, Helbich et al. (2014) shows that these relation are stronger for leisure trips than for work travels. Moreover they report that the

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http://dx.doi.org/10.1016/j.resconrec.2016.12.002
0921-3449/

Please cite this article in press as: Steeneveld, G.-J., et al., An urban climate assessment and management tool for combined heat and air quality judgements at neighbourhood scales. Resour Conserv Recy (2016), http://dx.doi.org/10.1016/j.resconrec.2016.12.002

significance of weather effects varies, specifically across settlement density.

The current study analyses overall (i.e. combination of both indoor and outdoor) exposures to naturally varying weather conditions and the added influences by anthropogenic contributions via the built environment, release of air pollution and in the long term via climate change. The exposure will be related to urban morphology and as such the study integrates natural and social sciences. We particularly concentrate on the budgets and flows of urban heat and air pollution.

Urban areas experience a different meteorology than the rural surroundings. Especially for clear sky and calm conditions cities are up to several degrees warmer than the countryside (Oke, 1982). These urban heat islands (UHI) are present in almost all urban areas and even relatively small towns may experience such an effect (Steeneveld et al., 2011a). The main causes of the UHI relate to structural and land cover differences between urban and rural areas (Stewart and Oke, 2012). Cities as a whole typically have a smaller albedo than rural areas. In addition, the sky view of the surface in urban areas is limited by buildings. Therefore there is a restricted emission of thermal radiation to space at night. Also, fabric, concrete and asphalt have a higher heat capacity than rural areas, resulting in a reduced cooling after sunset during the night. Moreover anthropogenic activities such as human metabolism, traffic, heating and cooling demand by buildings, electricity, and industry result in heat emissions (Souch and Grimmond, 2006; Krpo et al., 2010).

In addition to the heat effects, these weather conditions also support high atmospheric pollutant concentrations, in particular nitrogen oxides, ozone. The diurnal cycle of air quality is caused by both the dynamics of the atmospheric boundary layer and atmospheric chemistry. The boundary layer is shallow (50–200 m) during the early morning before sunrise. After sunrise the land surface is heated by solar radiation that consequently trigger atmospheric turbulence to grow the boundary layer to typical values of 1000–2000 m at the end of the afternoon. Hence pollutants are being diluted over a deeper layer at the end of the afternoon, and thereby diluting the concentrations. On the other hand the atmospheric chemistry of the ozone cycle is perturbed by release of ozone precursors by traffic, i.e. NOx, CO and volatile organic compounds in the rush hour. Once the sun reaches its maximum elevation the chemical processes are started due to the high radiation intensity which net converts the NOx to potentially harmful ozone concentrations in a time scale of 30 min to 1 h. The diurnal cycle of particulate matter peaks typically during the morning and afternoon rush hours, since motorized traffic is the main source in cities. This is on top of the fact that clear sky and calm conditions involve subsidence that traps the pollutants in the atmospheric boundary layer below the inversion. The occurrence of these processes on a regional/continental scale accumulate into a stock of air pollution which is (slowly) transported, which for the Northwestern Europe results in high peaks of advected air pollution. Both the raised pollutant concentrations and the urban heat island effect result in adverse health effects (Rainham and Smoyer-Tomic 2003;Tan et al., 2010) and reduced labour productivity (Hanna et al., 2011; Zander et al., 2015).

An enhanced understanding of the combined effects of the diurnal cycle of urban heat and air quality may affect citizens activities in order to minimize health effects. This would imply that outdoor activities should be planned in the early morning, and indoor activities are preferred during the day. The daily mobility patterns for cyclists and pedestrians should be adjusted as well, i.e. going to work earlier than normal during episodes. On the other hand mobility patterns from cars could be managed in such away that the precursors of ozone are emitted as least as possible.

The association between high temperatures and natural mortality has been documented several times (Smoyer, 1998; Baccini et al., 2008; Analitis et al., 2008; Anderson and Bell, 2009). The relation has often been shown as so called V- or J-shaped function, with the lowest mortality rates at moderate temperatures and rising progressively as temperatures increase or decrease (Huynen et al., 2001; Curriero et al., 2002). In the light of climate change this relation is a matter of increasing concern (e.g. Molenaar et al., 2016). The heat wave in 2003 in Western Europe has received much attention in particular. Several countries registered considerably elevated mortality numbers (Vandentorren et al., 2004, 2006; Conti et al., 2005; Garssen et al., 2005; Smargiassi et al., 2009).

In densely populated regions, the social, political, and economic space that separates cities and countryside are no longer distinguished by a clear urban–rural division (Stewart and Oke, 2012). Therefore it is hard to describe unique 'urban' and unique 'rural' reference states, and thus to unambiguously determine the UHI effect. Neighbourhoods can vary widely in their characteristics that influence the UHI. At the same time, rural conditions may vary across climate zones. In the remainder of the paper, UHI will refer to the temperature difference between urban local climate zones and the rural climate zone D (low grass, Stewart and Oke, 2012). Adaptation measures to minimize the UHI can range from modification of city design strategy and building material or introduction of vegetation (Synnefa et al., 2008; Mills, 2009), though its efficiency may vary with the present urban morphological structure. A quantification and assessment of the elevated health risk, caused by the UHI, can provide insight in the efficiency of adaptive measures (Bohnenstengel and co-authors, 2015). At the same time, one should realize that heatwave episodes often coincide with relative poor air quality. Hence the individual contributions of high temperatures and poor air quality to the mortality have not been unravelled. Also, a metric that combines these contributions is currently lacking.

In this paper we use a meteorological modelling study to investigate the effect of urban morphological parameters on UHI for a heat wave episode in 2006 in northwestern Europe. To assess health risks by high temperature, an analogue with the health risk of short-term exposure to ozone is made, and a single index for the combined effect is developed. In addition, the contribution of health risk by high temperatures is subdivided by a rural and an urban contribution. As such, a better scientific understanding of the health effects of combined exposure may assist in urban planning. This paper is organized as follows; Section 2 presents background material on the topic at hand and Section 3 outlines the methodology. Section 4 presents the results, and Sections 5 and 6 provide a discussion and concluding remarks.

2. Background

2.1. Heat index

The temperature in the city during a heat wave is determined by weather conditions at the regional level and the local urban environment. To assess health effects of heat in the city therefore two aspects are important, namely how public health risk increase as it gets warmer, and how the urban environment increases the risk or worsen the effects. We note that temperature alone is not sufficient to estimate heat stress, i.e. one has to consider all processes that affect the human energy balance and that may result in an unpleasant body temperature, like radiation, humidity, and wind speed play a role (Budd, 2001). To estimate heat stress, a variety of thermal indices have been developed. Examples are the wet bulb globe temperature that linearly combines air temperature and vapour pressure and the mean radiant temperature that