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Characterising the influence of atmospheric mixing state on Urban Heat Island Intensity using Radon-222

Scott D. Chambers [a,*], Agnieszka Podstawczyńska [b], Alastair G. Williams [a], Włodzimierz Pawlak [b]

[a] Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC, NSW 2232, Australia
[b] University of Łódź, Faculty of Geographical Sciences, Department of Meteorology and Climatology, Narutowicza 88, 90-139 Łódź, Poland

HIGHLIGHTS

- New application of a radon-based atmospheric stability classification technique.
- Novel approach for quantifying urban climate influences for all weather conditions.
- Convenient, economical tool for assessing efficacy of UHII mitigation strategies.
- Consistent way to compare urban climate effects across different regions and settings.

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ABSTRACT

Characterisation of the effects of varying atmospheric mixing states (stability) in urban climate studies has historically been hampered by problems associated with the complexity of the urban environment, representativity of measurement techniques, and the logistical and financial burdens of maintaining multiple long-term comprehensive measurement sites. These shortcomings, together with a lack of a consistent measurement approach, have limited our ability to understand the physical processes contributing to the urban heat island effect. In this study, we analyse 4 years of continuous hourly near-surface meteorological and atmospheric radon data from an urban–rural site pair in central Poland. A recently-developed radon-based stability classification technique, previously developed for urban pollution characterisation, is employed to characterise the Urban Heat Island Intensity (UHII) and other climatic factors over the full diurnal cycle by season and atmospheric mixing state. By characterising the UHII over a range of atmospheric mixing states in a statistically robust way, this technique provides an effective tool for assessing the efficacy of mitigation measures for urban climate effects in a consistent way over timescales of years to decades. The consistency of approach, ease of application, and unprecedented clarity of findings, provide a strong argument for atmospheric radon observations to be included as part of the 'standard measurement suite' for urban climate monitoring networks for non-coastal cities.

1. Introduction

More than half of the global population currently reside in urbanised areas (Cleugh and Grimmond, 2012; Baklanov et al., 2016), and the percentage of the global land area covered by urban environments is presently around 2–3% (Mills et al., 2010; Pandey et al., 2012; Cleugh and Grimmond, 2012). At the same time, it has long been established that urbanised and industrial landscapes can significantly alter their local climate (Howard, 1818; Memon et al., 2008; Grimmond et al., 2010; Fortuniak et al., 2014; Podstawczyńska, 2016; Theeuwes et al., 2016), although more thought needs to be given to meaningful classification of the surface characteristics of urban regions being investigated (Stewart and Oke, 2012). Urban Heat Island Intensity (UHII) is of particular interest for a number of reasons, not the least of which is its propensity to be exacerbated by the positive feedback introduced by the increase in energy consumption required to maintain what many urban residents have come to consider "an acceptable quality

* Corresponding author.
E-mail addresses: szc@ansto.gov.au (S.D. Chambers), apodstaw@uni.lodz.pl (A. Podstawczyńska), agw@ansto.gov.au (A.G. Williams), wpawlak@uni.lodz.pl (W. Pawlak).

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of life" (e.g. Robine et al., 2008; Grimmond et al., 2010; Mirzaei and Haghighat, 2010; Cleugh and Grimmond, 2012). Consequently, unless careful consideration is given to optimising urban planning, building design and construction, and energy use, urban heating effects will continue to increase (Saitoh et al., 1996; Grimmond et al., 2010; Cleugh and Grimmond, 2012). In the interests of minimising impacts on human health, and the associated costs, improvements are required in our understanding of the physical processes by which urban environments influence their local climate (such as the provision of robust *in situ* statistics for all components of the radiation, energy and trace gas budgets across a broad range of well-constrained atmospheric mixing states before and after the implementation of UHII mitigation measures). Such progress, however, is likely to be hampered until coordinated, systematic, consistent methods of quantifying and reporting urban climatic effects can be agreed upon (Mills et al., 2010; Mirzaei and Haghighat, 2010; Grimmond et al., 2010; Bassett et al., 2016).

The degree to which local climate is perturbed by urban development depends primarily on relative differences between the urbanised region and surrounding environment in (i) how much energy is available at the surface-atmosphere interface (the "net radiation"), (ii) how much additional energy is supplied as a result of anthropogenic activities, and (iii) how this combined energy is subsequently redistributed between atmospheric, terrestrial, or canopy processes. These contributing factors can be summarised in terms of the *radiation budget* and *surface energy balance* (Oke, 1995; Lemonsu and Masson, 2002; Memon et al., 2009), combined here in Eqn. (1):

$$(S_i - S_o) + (L_i - L_o) = Q^* = Q_H + Q_E + \Delta Q_S + \Delta Q_A - Q_F \quad (1)$$

where $S_{i,o}$ represent incoming and outgoing (reflected) shortwave radiation (W m^{-2}), $L_{i,o}$ the incoming and outgoing longwave radiation (W m^{-2}), Q^* the net radiation (W m^{-2}), Q_H the sensible heat flux, Q_E the latent heat flux, ΔQ_S the storage of energy within the urban volume (including air, trees, buildings, surfaces and soil), ΔQ_A net energy advection through the boundaries of the urban volume, and Q_F the anthropogenic energy release within the urban volume.

For an existing development, climatic differences between the urbanised region and its surroundings regarding net radiation and its redistribution at the surface can be attributed to a combination of controllable and uncontrollable factors (Memon et al., 2008, 2009). Controllable factors include, but are not limited to, urban planning (i.e. "canopy" characteristics and building design/construction materials), population density, and energy consumption (Atwater, 1972; Oke, 1995; Saitoh et al., 1996; Memon et al., 2008; Cleugh and Grimmond, 2012). Examples of uncontrollable factors, on the other hand, include location (e.g. proximity to the coast, or topographic setting) and prevailing regional meteorology (e.g. wind speed, cloud cover, etc.).

As population densities and urban spread continue to increase, mitigation of urban heating effects is becoming a greater concern (Memon et al., 2008; Mills et al., 2010; Cleugh and Grimmond, 2012; Chapman et al., 2013). Numerous measures to reduce energy consumption and change the surface energy balance of existing and newly-planned developments are being investigated (Akbari et al., 2001; Memon et al., 2008; Mills et al., 2010 and references therein; Botham-Myint et al., 2015; Touchaei and Akbari, 2015). To better enable urban planners to optimise the cost-benefit ratio of the available mitigation measures, a clearer understanding of urban climatic influences is required for all seasons and a range of atmospheric mixing states. However, in order to properly assess the need for, and efficacy of, individual mitigation measures for factors that *are* controllable, it is first necessary to adequately understand and characterise the influences from factors that *are not* controllable.

The regional (≤synoptic scale) atmospheric mixing state strongly influences the intensity of urban climatic effects, as evidenced by numerous studies indicating that urban heating effects are most pronounced at night under anti-cyclonic (clear-sky, low wind) conditions (e.g. Oke, 1995; Pongracz et al., 2006; He et al., 2013). In conjunction with the requirements of remote sensing investigations (Memon et al., 2009), the focus of many studies on purely clear-sky conditions this has led to a strong bias in the literature (e.g. Lemonsu and Masson, 2002; Fortuniak et al., 2006, 2014; Pal et al., 2012). The tendency to "cherry pick" ideal conditions for UHII investigations, or to simply "lump all available conditions together" as annual averages, has given rise to two significant problems: (i) a substantial under-representation of the full range of atmospheric conditions, and (ii) statistics for ideal meteorological cases that are not particularly robust. Inadequate statistical representation in UHII studies can result in significant errors due to the intermittency of some meteorological events at a range of temporal scales, as mentioned by Fortuniak et al. (2006); Nelson et al. (2007) and Mills et al. (2010). This is of particular concern if observations are then used to evaluate the performance of urban simulations.

Numerous conventional meteorological methods are presently available to characterise the atmospheric mixing state or "stability" (including Obukhov Length, Richardson Number, Pasquil-Gifford schemes; e.g. Pasquill and Smith, 1983; Foken, 2006), which vary widely in terms of their accuracy, cost, region/limits of applicability and ease of implementation. In recent years, the use of atmospheric radon measurements for this purpose has also achieved considerable credibility (Perrino et al., 2001; Chambers et al., 2015, 2016; Williams et al., 2013, 2016). Radon-222 is an unreactive, poorly soluble, naturally-occurring radioactive gas which has – for the purposes of atmospheric stability investigations – an exclusively terrestrial source function that is relatively uniform on local to regional scales. Furthermore, since Radium-226 (the parent of radon) has a half-life of 1600 years, seasonal source characteristics of radon exhibit little long-term variability. Radon's short half-life (3.8 days) prevents it from accumulating in the atmosphere on greater than synoptic timescales, yet renders its concentrations approximately conservative on hourly to nightly timescales. These characteristics make radon an ideal tracer within the atmospheric boundary layer (ABL), and ensure that its near-surface concentrations are directly linked to the outcomes of vertical mixing processes in the lower atmosphere.

In this study we use 4 years of paired hourly meteorological and atmospheric radon observations, within and outside the city of Łódź, Poland, to accurately characterise the influence of meteorological factors on near-surface (canopy-level) climatic differences observed between the urban centre and surrounding agricultural land. We apply a recently-developed radon-based stability analysis technique, until now restricted to urban pollution studies, to this urban climate problem. The rural radon observations are used to characterise the regional atmospheric mixing state, which is considered to be perturbed locally by the urban canopy. We demonstrate the ability of this approach to provide robust statistical distributions of canopy-level UHII, absolute humidity, and wind speed, over the full diurnal cycle for a range of atmospheric mixing states in all seasons. The ability to accurately characterise the influence of "uncontrollable" meteorological factors in this way provides a sound foundation for (i) defining benchmarks for UHII influences and the subsequent evaluation of the efficacy of UHII mitigation measures, and (ii) more detailed analyses of the influence of the urban canopy on boundary layer mixing processes; which will be the focus of future separate investigations.