Remote Sensing of Environment 186 (2016) 637–651

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Thermal infrared remote sensing of urban heat: Hotspots, vegetation, and an assessment of techniques for use in urban planning

Andrew M. Coutts [a,b,*], Richard J. Harris [a], Thu Phan [a], Stephen J. Livesley [c], Nicholas S.G. Williams [c], Nigel J. Tapper [a,b]

[a] School of Earth, Atmosphere and Environment, Monash University, Australia
[b] CRC for Water Sensitive Cities, Australia
[c] School of Ecosystem and Forest Sciences, University of Melbourne, Australia

ARTICLE INFO

Article history:
Received 17 August 2015
Received in revised form 12 August 2016
Accepted 12 September 2016
Available online 3 October 2016

Keywords:
Urban climate
Planning tools
Thermal infrared remote sensing
Urban greening
Heat mitigation

ABSTRACT

In order to mitigate areas of high urban air temperature (or 'hotspots'), advice and tools are currently being sought to help inform urban planning and decision making around urban greening. One potential tool receiving growing interest is the use of thermal imagery for identifying hotspots, however this relies on the assumption that patterns in land surface temperature (LST) coincide with patterns in air temperature. This study explores the capacity of very high resolution (VHR), airborne thermal infrared (TIR) remotely sensed data to identify hotspots at a neighbourhood and street scale resolution. As such it assesses whether VHR TIR remote sensing is an appropriate tool for urban planning and urban greening decision making. In partnership with a local municipality in Melbourne, Australia, VHR (0.5 m) daytime and night time TIR images were captured during warm summertime conditions in February 2012. We found that VHR TIR data certainly identified locations of high LST that could be prioritized for urban greening, however at very high resolutions, VHR TIR data could not identify hotspots because patterns in LST did not strongly correlate with patterns of high air temperature. When VHR TIR data was aggregated to a coarser resolution, it could be used at the neighbourhood-scale to identify hotspots due to greater confidence that areas of high LST do represent air temperature hotspots. Increased vegetation proportion was associated with a reduction in LST for both the day and night meaning urban greening can be used to mitigate hotspots and should be prioritized in wide, open streets where building shade is less. While VHR TIR remote sensing may be an attractive option, this study shows it is not a suitable tool to help inform urban planning and urban greening decision making as the capture, post-processing and interpretation requirements and costs of delivering a high quality product are prohibitive for many end users. We suggest that those seeking to use thermal imagery to identify hotspots in the urban landscape, strongly consider more accessible and cheaper satellite remote sensing products (such as Landsat). VHR TIR derived LST may be useful in designing urban spaces for improved human thermal comfort and focusing on a small region of interest, but the numerous complexities and limitations of the data must be recognized.

1. Introduction

Increasing urban vegetation is widely recognized as a key approach to mitigating urban heat through evapotranspiration and shading (Dimoudi and Nikolopoulou, 2003; Chen and Wong, 2009). Several studies have modelled a reduction in air temperature from an increase in urban vegetation cover (Zhou and Shepherd, 2010; Loughner et al., 2012; Rosenzweig et al., 2009), while satellite remote sensing studies have demonstrated that greater vegetation cover corresponds with reduced land surface temperature (LST) (Li et al., 2012; Rogan et al., 2013; Klok et al., 2012). Ensuring that urban areas have sufficient vegetation cover and regular distribution of vegetated open space is important to reduce daytime heat storage in the urban environment (Honjo and Takakura, 1990). Further, maintaining adequate soil moisture via irrigation and water sensitive urban design is desirable to support healthy vegetation and promote evapotranspiration (Goldbach and Kuttler, 2012; Coutts et al., 2013). Urban planners and designers are recognizing the growing need to create more attractive, thermally comfortable and sustainable cities, especially as urban populations expand and climatic variability and extremes increase.

In response to elevated urban temperatures and the knowledge of relations between high urban air temperature and adverse heat-related health outcomes (e.g. mortality and heat related illness) (Loughnan et al., 2013), local municipalities are exploring how to best implement urban greening to improve urban climates. Unfortunately, there is little practical guidance available, and as Bowler et al. (2010) concluded from

* Corresponding author at: School of Earth, Atmosphere and Environment, Monash University, Room 205, Building 28, Wellington Rd, Clayton, Victoria, 3800, Australia.
E-mail address: Andrew.Coutts@monash.edu (A.M. Coutts).

http://dx.doi.org/10.1016/j.rse.2016.09.007
0034-4257/

a review of urban greening for cooling in cities: *"The current evidence base does not allow specific recommendations to be made on how best to incorporate greening into an urban area"* (pg 147), though recent research has begun to address this void (Norton et al., 2015). The lack of guidance presents a problem because limited funds are available to city or municipal governments to establish and maintain public green space and street trees over the long term, so prioritizing investment to achieve heat mitigation objectives is paramount. Urban planners and designers need readily accessible, cheap and rapidly available tools to support decision making processes.

In a bid to inform heat mitigation strategies and the prioritized implementation of urban vegetation cover, some local municipalities are investigating the use of thermal imagery as a tool to identify 'hotspots'. Hotspots are defined here as areas of relatively higher air temperature (T_a). Using thermal imagery to identify hotspots relies on the assumption that areas of high T_a coincide with areas of high LST (i.e. higher LST leads to higher T_a, which leads to higher risk of heat stress). Aniello et al. (1995) used Landsat Thematic Mapper (TM) satellite data (120 m) to map LST in Dallas, Texas, noting that areas of high LST occurred most frequently where tree cover was lacking, such as business districts and shopping complexes. In contrast, a number of local municipalities in Australia have experimented with very high resolution (VHR) (e.g. < 5 m), airborne thermal infrared (TIR) remote sensing to inform greening strategies and tree placement as it provides a very detailed spatial picture of the LST of the urban surface. Previous studies using VHR TIR data have identified important landscape features that influence LST including the amount of sealed (impervious) surfaces (Kottmeier et al., 2007), the irrigation of green space and amount of tree cover (Spronken-Smith and Oke, 1998), and street geometry (Bärring et al., 1985). VHR TIR remote sensing can potentially provide detailed information for targeted urban greening at the household and street-scale and is an excellent communication tool for local planning authorities and residents.

Despite the attractiveness of VHR TIR remote sensing, the collection, analysis and interpretation of the data are not straight forward, and there are several limitations. Again, TIR remote sensing provides a spatial picture of LST rather than T_a and a key assumption is that patterns in LST can be used as a surrogate for patterns in T_a. Saaroni et al. (2000) observed similar patterns in surface and air temperatures using high resolution (2 m) airborne TIR remote sensing in Tel Aviv, Israel. Similarly, Nichol et al. (2009) measured a close relationship between the surface and air temperature in Hong Kong (ASTER satellite data, 90 m resolution). However, others state there is no simple, general relation between measured air temperature and remotely sensed LST data (Voogt and Oke, 2003; Tomlinson et al., 2011).

Several other issues should be considered in the collection and application of VHR TIR remote sensing data for urban planning. Industry providers of VHR TIR data may or may not have tested, calibrated, or evaluated their TIR camera for an urban landscape scenario. What is often provided is an image of surface brightness temperature that has not been corrected for atmospheric effects or emissivity. Correction for emissivity needs to occur but is difficult at such high resolutions because individual surface types are identifiable and are highly varied. Correcting VHR TIR remote sensing data using a uniform emissivity value (e.g. Pu et al., 2006) is not appropriate, while Temperature – Emissivity Separation algorithms (e.g. Gillespie et al., 1998) require multiple bands in the thermal spectral range in order to be applied. Also, TIR data depends on the viewing angle of the sensor and airborne based plan (bird's eye) views of the surface often neglect the LST of walls and obstructed surfaces such as below tree canopies (Voogt and Oke, 2003), all of which contribute to the microclimate of the urban canopy layer (the layer of air below the mean height of buildings and vegetation). The complex nature of the urban surface due to large buildings and other urban structures results in highly variable patterns of LST. This leads to directional variations in outgoing longwave radiation from these surfaces (thermal anisotropy) (Voogt and Oke, 1998) which influences observed radiances and is also often ignored. Furthermore, the low temporal frequency of VHR TIR data capture should also be considered, as LST patterns will vary greatly over time with changes in thermal admittance, surface moisture, net radiation, and differences in near-surface atmospheric conditions (Voogt and Oke, 2003). Without a consideration of these various issues, there is a risk of misinterpretation of TIR data (Roth et al., 1989).

In collaboration with a local municipality, this study explores the potential application of VHR TIR remote sensing to identify hotspots and inform urban land use planning and strategies for heat mitigation using urban greening. The aim of urban greening is to intentionally modify surface radiative and energetic processes by replacing impervious urban surfaces of high thermal admittance with trees, green walls and green roofs (that are well supplied with water) that have lower thermal admittance than urban surfaces and allow infiltration into the soil. As a result, heat conduction is reduced and evapotranspiration is promoted leading to reduced LST. The combination of reduced LST and greater evapotranspiration means there is less sensible heating of the atmosphere, thereby improving the thermal environment for urban populations. Trees are particularly effective as they provide shade to urban surfaces and can access deep water reserves (Coutts et al., 2013). Using VHR TIR remote sensing captured during a heatwave, we explore relationships between LST and vegetation cover, and associations between LST and near surface T_a. Drawing primarily on VHR airborne TIR remote sensing, and supported by satellite TIR remote sensing, this study seeks to investigate the following questions:

1) Can VHR TIR remote sensing be effectively used to identify hotspots (areas of relatively high T_a) at the neighbourhood-scale and the street-scale and where to prioritise urban greening?
2) How does vegetation cover influence VHR TIR derived LST and the potential development of hotspots?
3) Is VHR TIR remote sensing a suitable tool to provide appropriate information to inform urban greening interventions for urban heat mitigation?

In tackling these questions, we seek to provide guidance on how useful TIR remote sensing can be for urban planning, the most effective approaches for collecting and applying TIR remote sensing data, and an understanding of what can be achieved given the limitations. This guidance is provided with a focus on the end user, such as local municipal staff, and their capacity to appropriately acquire, interpret and apply remotely sensed TIR data for use in urban land use and heat mitigation planning.

2. Methodology

2.1. Acquisition of high resolution TIR remote sensing data

The City of Port Phillip (CoPP), a local municipality in Melbourne Australia, commissioned VHR, airborne TIR remote sensing in the summer of 2011–12. The objective was to use this high resolution TIR data to inform the implementation of a policy of increased tree canopy cover, by identifying the hotspots within their municipality using thermal imagery and then prioritise these for cooling through urban greening (CoPP, 2010). A collaborative project was established between CoPP, adjacent local municipalities, the Victorian state government, consultants and university researchers in a bid to explore and draw as much value from the thermal imagery as possible. This collaborative project sought to establish a guide for local and state governments on the use and applicability of high resolution TIR for heat mitigation and adaptation planning in urban landscapes. For this purpose, hotspots are defined as areas of relatively high T_a, meaning any urban greening implementation based on thermal imagery relies on the assumption that areas of high LST coincide with areas of high air temperature. This assumption will be tested here.