Urban Climate News

Quarterly Newsletter of the IAUC

Issue No. 58 December 2015 • www.urban-climate.org • International Association for Urban Climate

From the IAUC President

Colleagues – Welcome to the 58th edition of the *Urban Climate News*. This issue provides a Feature report by Lee Chapman on Urban Meteorological Networks, a number of Project reports by some of our ICUC-9 student award winners, special reports on three recent workshops plus a new 'working group' on outdoor thermal comfort and our regular features "In the News" and new Bibliography additions. Thanks to all our contributors, and to Editor David Pearlmutter for putting together this issue.

I recently had the honour and pleasure of participating, along with a number of other IAUC members, in the Croucher Advanced Study Institute, which was hosted by Professors **Edward Ng** and **Chao Ren** and their team at the Chinese University of Hong Kong. This event, sponsored by IAUC, provided participants with a series of lectures in two themes under the title "Changing Urban Climate and the impact on Urban Thermal Environment and Urban Living". The first theme, led by Professor Janet Barlow, included four lectures on "Urban Climate" and the second theme, led by Professor Richard de Dear, featured four lectures focused on "Urban Comfort". The closing guest lecture on the "Healthy City", by Professor Chris Webster, Dean of the Faculty of Architecture at the University of Hong Kong, provided a very interesting interdisciplinary perspective on the broader urban environment to which urban climatological and meteorological research contributes. The ASI was followed by a WUDAPT workshop focusing on the growth of Chinese cities, led by Gerald Mills and the WUDAPT team. Special reports on the ASI and the WUDAPT workshop are available in this edition of the newsletter.

The ASI format, which provides for longer lecture slots and dedicated discussion periods, allows an element of 'teaching' that is not often accommodated by traditional conference formats. The presentations for this, along with an earlier ASI, will be available on the web. These provide a nice legacy for the ASI and a useful teaching and learning resource of IAUC members. We will post the links from our "Resources" page on the IAUC website. Congratulations to Edward, Chao and their team for this success. More generally, on the subject of teaching and learning materials, I would like to encourage other IAUC members who may be hosting similar events or who may have teaching/learning materials broadly applicable to IAUC members that they would like to share to contact me about making these available via our website – I would like to grow this part of the IAUC resource.

At the ASI event, a new 'Working Group' on Protocols for the Assessment and Reporting of Outdoor Thermal Comfort was announced (see report by Rohinton Emmanuel in this newsletter). We have set up a discussion group on the IAUC webpages to help facilitate this Working Group and IAUC members who are interested are invited to participate.

Finally, thank you to all IAUC members who participated in the ICUC-10 site survey and to our Secretary David Sailor for conducting the survey; the Board will be making deliberations in the New Year on the location for ICUC-10.

Since this is the final issue for 2015, let me close by thanking everyone who has contributed to, and participated in, IAUC and ICUC-9 events and activities over the past year. Best wishes for a happy, healthy and prosperous 2016.

– James Voogt,
IAUC President

javoogt@uwo.ca

Inside the Winter issue...

COP21: City mayors discuss green solutions in Paris

Cities could use water from rivers and the sea to stay cool as the climate heats, city mayors have been told

December 2015 — Carbon emissions from air-conditioning are expected to soar as temperatures climb and people become richer.

But at a global mayors summit, Paris was showcasing a simple technology using water piped from the Seine to cool apartments near the Champs Elysees.

London Mayor Boris Johnson said he wanted London to follow suit by cooling buildings using water from the Thames. "I don't like to admit it – but the French are ahead of us on this," he confessed.

The system works by taking water from the river and piping it round people's homes like ordinary piped water air conditioning. In summer a heat pump is used to make the water even cooler by employing technology similar to a fridge.

The mayors meeting in Paris City Hall was timed to coincide with the UN climate summit. It brought together half of the 80 mega-city mayors who are working together to tackle climate change.

The chairman of the group, Eduardo Paes, Mayor of Rio, said the mayors represented 600m people and a quarter of the global economy. "We can be very effective," he said. "Sometimes governments move slowly – we can often move more quickly."

The mayors said they had learned from each other to spread green solutions round the world. They claim to have collectively made 10,000 climate initiatives since 2009.

They spoke about their favourite initiatives:

- Gregor Robertson, Mayor of Vancouver, said that in car-dominated North America more than half of people were now using what he calls "active transport" – walking, cycling and mass transit.
- Frank Jensen, Mayor of Copenhagen, said 99% of homes in his city were warmed by district heating, in which a network of premises are served by one efficient central heating system. He said this had more than halved carbon emissions since 1995.
- Clover Moore, Mayor of Sydney, said the city had saved cash and cut emissions by 40% after she learned about low-energy lighting from the Mayor of Los Angeles. "Working together, it's powerful action across the world," she said.
- Alfred Okoe Vanderpuije, Mayor of Accra, said Ghana was being plagued by severe and erratic rains which he believed were linked to climate change. "Usually our rains are in July and February… but it's raining now." Tough decisions had to be made, he said, to clear slum dwellers so water courses could be unblocked.
- Karin Wanngård, Mayor of Stockholm, said the city would be fossil fuel free by 2040. A new city area with 12,000 houses would generate more energy than it uses by 2030. "Mayors can really make a difference – we can push boundaries," she said.

Top: The world's largest solar boat is currently moored on the Seine. Bottom: Global mayors in Paris City Hall. ***Source:*** http://www.bbc.com

Boris Johnson's team said since the Mayor was elected in 2008, carbon emissions in London were down by 14%, even though population had swelled.

He said a major preoccupation was to find ways of finding a low-carbon way to provide the heating and cooling from natural gas, which made up nearly 50% of the city's emissions.

Darren Johnson, Green member for the London Assembly, told BBC News: "On the whole Boris Johnson has been a real disappointment. He has expressed climate sceptic views and failed to meet most of the targets in his (climate) strategies."

The global commission advised by Lord Stern concluded recently that climate change could only be tackled if new cities to house a burgeoning population could be planned less like Los Angeles and more like Paris.

— *By Roger Harrabin, BBC environment analyst.* http://www.bbc.com/news/science-environment-34999962

Sustainable Cities and Buildings at COP21: Delivering Our Future Today

December 2015 — This year marks the first-ever Buildings Day at the annual climate talks. At COP21 in Paris, leaders from around the world and all sectors will launch a new Global Alliance for Buildings and Construction and discuss how to transform the buildings sector to become part of the low-carbon urban economy of the future. One-third of global greenhouse gas emissions are due to energy use in buildings, and building-related emissions are expected to double or even triple by 2050 without action.

In part, this is due to rapid urbanization: We are adding 250,000 people to our cities each day. In India alone, more than half of the buildings that will exist in 2030 did not exist in 2010. Unless we are deliberate in the way we design, construct and renovate buildings, we could lock-in our cities to inefficient energy use for decades to come. Energy waste by buildings burdens our citizens with higher energy bills, air pollution and carbon emissions.

What's the challenge? We must act now, yet most countries have not focused on energy waste by buildings. A review of building efficiency in countries' national climate plans (known as INDCs) finds fewer than 50 countries provided details on how they would tackle building energy efficiency. It's time to turn our attention not only to the important issues of energy supply, but also to the equally critical need to ensure that every kilowatt hour delivered is used efficiently. Energy waste in buildings is something no country or city can afford.

The IEA estimates that an additional $220 billion is needed by 2020 - an almost 50 percent increase on 2014 investment in energy efficient buildings.

The good news? We have options. Technologies and practices commercially available today can shift our emissions trajectory.

Global change on building efficiency requires local action and a broad coalition of city regulators, businesses and financing institutions. From Bogota to Bangkok, cities are poised to move forward. ICLEI's recent review of the commitments made by 608 subnational jurisdictions in the carbonn® Climate Registry found that roughly half of the 1,293 commitments are supported by actions in the building sector. To speed and scale action, cities are reaching out seeking technical support, looking for trusted advisors and working with the private sector to deliver change.

In support of this agenda, The Global Environment Facility, in partnership with World Resources Institute (WRI) and the UN Environment Programme (UNEP), announced the expansion of the Building Efficiency Accelerator (BEA). This commitment of new funding will catalyze an increase in energy-efficient buildings in developing country cities.

The BEA is working in partnership with the UN Sustainable Energy for All Energy Efficiency Platform and the Global Alliance for Buildings and Construction. It will engage 50 cities on issues of policy implementation, most importantly building codes, but also project development, and tracking and monitoring of building efficiency.

Of those, six cities will work with the partnership in a more intensive, multi-stakeholder process to help align policies and markets. Interventions will focus on codes and standards; targets; certifications; financial mechanisms; government leadership; and benchmarking and disclosure.

Each of the 30 cities that joins the Building Efficiency Accelerator will:

1) Commit to implement a new policy or update existing policies;
2) Undertake a project such as retrofits or construction of efficient new buildings; and
3) Measure and communicate its progress against energy and climate goals.

Mayor Mancera of Mexico City, for example, announced at Buildings Day that it is moving forward to integrate building energy performance in local construction codes, retrofitting hospitals with solar hot water and efficiency measures, and auditing and retrofitting municipal buildings. More than 100 stakeholders have participated in WRI Ross Center for Sustainable Cities' workshops and working groups to provide input and recommendations on how to implement local codes and advance retrofits. The goal? To help meet their ambitious climate targets and improve the performance and competitiveness of the city.

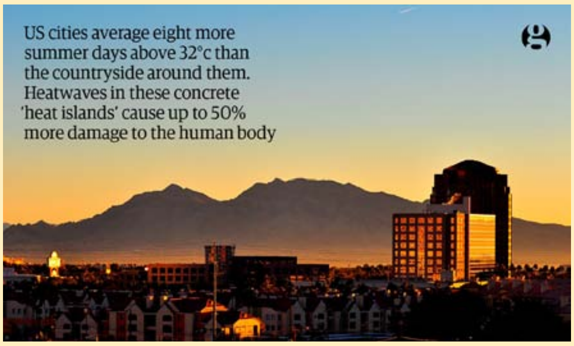
We are proud these activities will support the new Global Alliance for Buildings and Construction as we shine a spotlight on the potential for real change that can help improve buildings and the lives of people in cities around the world.

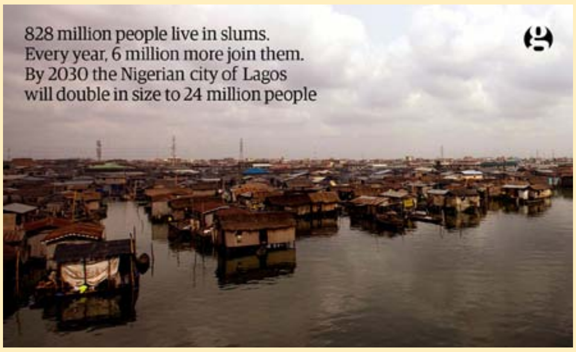
How we plan and design our future cities can have major impacts. This is an important reason why the GEF recently launched a $1.5 billion sustainable cities project to support city planning, initially in 23 cities in 11 developing countries.

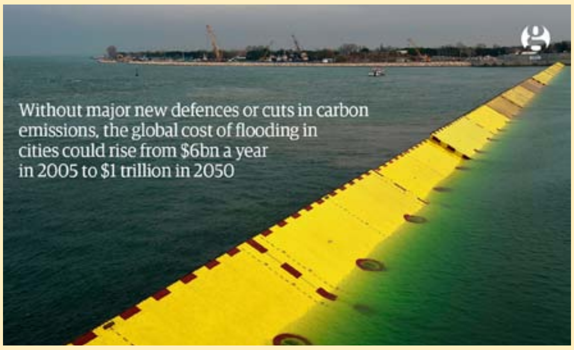
With the build-out of our cities we must act now to create a culture of urban efficiency around the world.

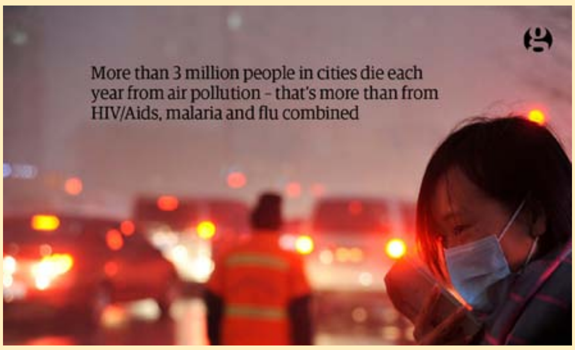
— By Dr. Andrew Steer, President and CEO World Resources Institute, and Naoko Ishii, CEO and Chairperson, Global Environment Facility. Source: http://www.huffingtonpost.com/dr-andrew-steer/sustainable-cities-and-buildings-at-cop21-delivering-our-future-today_b_8707866.html

10 reasons why cities hold the key to climate change & global health









www.theguardian.com/cities/gallery/2015/dec/08/statistics-show-cities-key-future-planet-un-climate-change

China's vacuum-cleaner artist turning Beijing's smog into bricks

As another coal-fuelled 'airpocalypse' engulfs northern China, Nut Brother hopes his 'smog bricks' will raise awareness

December 2015 — His idol is Subcomandante Marcos, the masked Mexican rebel; his weapon of choice a 1,000-watt vacuum cleaner.

Meet Nut Brother, the Chinese activist-artist attempting to vanquish toxic smog by sucking it up through a black plastic nozzle.

As the latest coal-fuelled "airpocalypse" engulfed northern China this week and world leaders gathered in Paris to debate the fight against climate change, Nut Brother hit the streets of Beijing hoping to raise awareness of his country's deadly smog crisis.

For the last 100 days, the activist, whose real name is Wang Renzheng, has used the industrial appliance to extract dust and other lung-choking pollutants from the city's atmosphere before transforming them into a dark brown "smog brick".

"I want to show this absurdity to more people," Wang, 34, said on Tuesday as pollution levels in the Chinese capital soared to levels 40 times higher than those deemed safe by the World Health Organisation.

This combination of photographs taken on 1 November this year, top, and 1 December, show pedestrians in Beijing amid widely differing levels of air pollution. ***Source:*** http://www.theguardian.com

Wang Renzheng, a Chinese performance artist better known as Nut Brother, with the industrial vacuum cleaner he uses to suck up smog. ***Source:*** http://www.theguardian.com

"I want people to see that we cannot avoid or ignore this problem [and] that we must take real action." Until the onset of this winter, Beijing's 20 million long-suffering residents had expressed some optimism that things were on the up, after a comparatively smog-free 2015.

But the city's latest "airmageddon" – to which the Chinese president, Xi Jinping, made no reference during his address to the UN climate summit in Paris on Monday – has underlined the scale of the challenge that remains.

Despite government claims that "effective measures" had been taken to combat the hazardous smog, China's capital has for days been coated by a putrid, nicotine-coloured haze.

"You can't tell if it is night or day!" Liu Haishan, 38, a taxi driver, complained on Tuesday afternoon as he attempted to navigate through the gloom.

Beijing authorities claimed they had forced vehicles off the roads and shut more than 2,000 polluting companies in order to tackle the crisis.

But environmentalists attacked the government for failing to declare a pollution "red alert", despite the appalling conditions.

"The shocking levels of air pollution we have seen in the last few days are a serious danger to the health of hundreds of millions of citizens," said Dong Liansai, Greenpeace's climate campaigner in China. "Moreover, the Beijing city government's insufficient alerting system has compounded the problem."

Nut Brother said he began plotting his one-man anti-smog campaign in 2013 when a now infamous spell of pollution – dubbed China's inaugural "airpocalypse" – saw flights grounded, motorways closed and hospitals packed with wheezing patients suffering from respiratory complaints.

"It's not healthy," the artist said of the smog, which scientists blame for about 4,000 deaths a day in China, most caused by heart and lung problems and strokes. "You have nowhere to hide. It is in the air all around us.

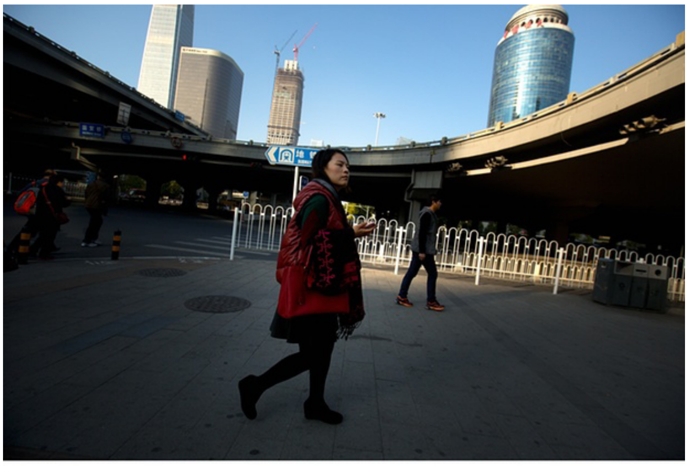
"Nut Brother, who was born in Hubei province and is based in the southern city of Shenzhen, began to execute his plan in July after convincing a restaurant owner to contribute 10,000 yuan (£1,000) to his pollution-themed performance art project.

He ordered a vacuum cleaner from a manufacturer in Shanghai and began taking it on four-hour sorties across Beijing's urban sprawl, gobbling up pollutants as he went. Photographs published in the Chinese media this week showed him pushing his vacuum cleaner past some of Beijing's most celebrated landmarks. One image shows him sucking up dust outside Rem Koolhaas's cloud-puncturing China Central Television headquarters; in another he is seen strolling past the portrait of Mao Zedong at the entrance to the Forbidden City.

Nut Brother said his attempts to suck up smog from Tiananmen Square – perhaps the most heavily guarded public space on earth – had triggered his only brush with the law. "They sent a plainclothes policeman to follow me but they didn't impede my movements," he recalled.

Chinese websites and social networks were covered

The same spot in Beijing on 1 November and 1 December. *Source:* http://www.theguardian.com



Pedestrians by an elevated highway in Beijing on 1 November, top, and 1 December 2015. *Source:* http://www.theguardian.com

with reports of the artist's quirky smog-harvesting campaign on Tuesday in Beijing. Reporters flocked to the artist's temporary home – a 60-yuan-a-night youth hostel near the Lama Temple – to see his vacuum cleaner up close. "It is terrible today," he complained of the latest bout of severe pollution, Beijing's worst of the year.

Despite grabbing headlines this week, China's unconventional environmentalist remains a relative enigma. "I'm passionate about the environment but I don't know if that qualifies me as an activist," he said when asked how he defined himself. "I think I'm a normal person, just like anyone else." In a 2012 interview with the Shenzhen Daily, Nut Brother said his "spiritual idol" was Subcomandante Marcos, the essay-writing, rifle-toting leader of Mexico's Zapatista rebel group.

On Tuesday, the artist conceded it would take more than one vacuum cleaner to purify China's skies. But he said he hoped to bring some of the Zapatista leader's creativity to one of his homeland's most pressing problems.

"[Subcomandante Marcos] used imaginative ways to change society," Nut Brother said. "That is the path I want to follow." *Source:* http://www.theguardian.com/world/2015/dec/01/chinese-vacuum-cleaner-artist-turning-beijings-smog-into-bricks

Urban Meteorological Networks: An Urban Climatologist's Panacea?

By Lee Chapman (l.chapman@bham.ac.uk)
School of Geography, Earth & Environmental Science
University of Birmingham, UK

"In the next century, planet earth will don an electronic skin. It will use the Internet as a scaffold to support and transmit its sensations. These will probe and monitor cities, the atmosphere, highways, conversations, our bodies, even our dreams." —Neil Gross (1999)

Introduction

In-situ observations from climate networks have provided the most important basis for the detection and attribution of the causes of climate change to date (IPCC, 2001). However, national global networks have limited instrumentation in urban areas, as they are considered unrepresentative of the broader climate. With over 50% of the world's population now residing in cities (UN, 2009: www.un.org/esa), it is now essential to better understand atmospheric processes and impacts in urban areas and how they will be affected by climate change.

Urban modifications to climate, such as the Urban Heat Island (UHI) effect, are well documented and studies have increased our understanding, yet the basic measurement of climate variables across urban areas remains very limited (Chapman et al., 2015). The existing monitoring paradigm deploys small numbers of high precision sensors, where the site numbers are limited due to the associated costs (e.g. equipment, personnel, management, maintenance). This results in just a couple of sites per city, making upscaling a considerable challenge.

An alternative approach is to saturate the environment with cheaper, lower grade instrumentation – acknowledging the presence of local microclimates or uniqueness of place (Bevan, 2000), albeit at the consequence of the accuracy or precision of individual measurements. As a result of technological and communication advancements as well as a new generation of low-cost sensors of comparable quality to research-grade instrumentation (Young et al., 2014), our ability to make meteorological measurements is unprecedented. As a result, high-density sensor networks can be used to monitor cities in a way that has previously been impossible.

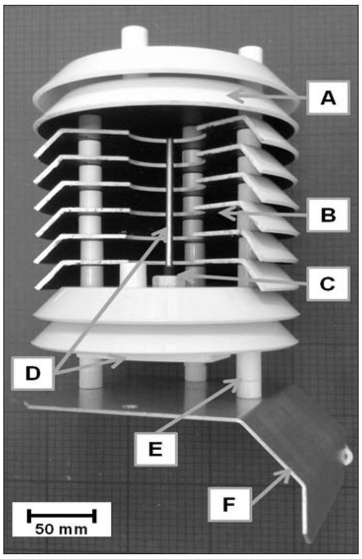
Urban Meteorological Networks

This high-resolution approach is now starting to find favour within urban climatology, as the original paradigm was limiting climatological research. Numerical weather prediction and urban climate models continue to suffer from insufficient observation data to be adequately initialised and verified in cities across the world (Grimmond et al., 2010; NRC, 2010). Overall, it is accepted that the current 'standard' approach to measuring climate is not sufficient to resolve the mosaic of microclimates and associated vulnerabilities experienced in urban areas. High resolution data is needed to improve hazard warning systems (e.g. NRC, 2010), flood-water and urban drainage management (e.g. Arnbjerg-Nielsen et al., 2013) and UHI monitoring (e.g. Tomlinson et al., 2013).

As a result, an increasing number of Urban Meteorological Networks (UMNs – see Muller et al., 2013 for a full review) of differing size and scales are being implemented in and across cities as part of 'Smart City' initiatives and other research projects (e.g. Birmingham Urban Climate Laboratory: Chapman et al., 2015; Oklahoma City Micronet: Basara et al., 2010; the Helsinki Testbed: Koskinen et al. 2011).

Box 1: The Birmingham Urban Climate Laboratory

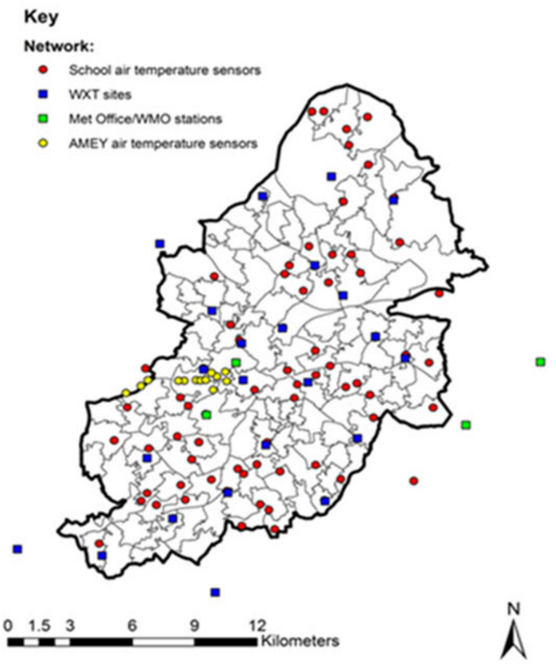
The Birmingham Urban Climate Laboratory is a near real-time, high-resolution Urban Meteorological Network containing automatic weather stations and non-standard air temperature sensors organised in two arrays:

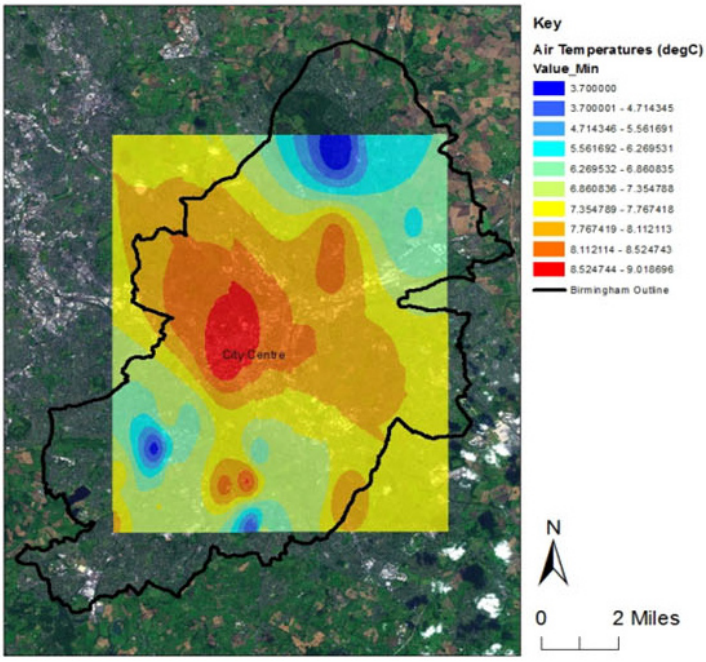


IoT air temperature sensor

- **Coarse Array (Automatic Weather Station testbed)**: Twenty-five Vaisala WXT520 Weather Transmitters and Skye SKS1110 pyranometers, as well as three standard and one non-standard Met Office/WMO meteorological sites are located in a coarse array (approximately 1 per km^2) across Birmingham. Variables measured are air temperature, relative humidity, wind speed, wind direction, atmospheric pressure, precipitation and solar radiation.
- **Wide Area Array (low cost temperature sensors)**: Over 70 low cost (approx. $100) air temperature sensors are nested within the Automatic Weather Station testbed. These self-contained sensors are based on an Internet of Things approach and contain a wireless communications card, flash memory and sufficient power from a Lithium-Thionyle Chloride battery to last for three years. The sensors use existing WiFi networks to send data to the cloud in real time, thus bypassing expensive communication costs. The sensor was thoroughly tested against existing standards by Young et al (2014) where a comprehensive overview can be found.

In summary, BUCL is novel in its density (below), the low-cost nature of the sensors and the use of proprietary WiFi networks to significantly reduce communication costs.





Birmingham Urban Climate Laboratory Sites (left) currently in operation and (right) sample interpolation of minimum air temperatures during a heatwave event.

Figures taken from: Chapman L, Muller CL, Young DT, Warren EL, Grimmond CSB, Cai X-M, Ferranti EJS. (2015) The Birmingham Urban Climate Laboratory: An open meteorological testbed and challenges of the smart city. *Bulletin of the American Meteorological Society* 96:1545-1560. ©American Meteorological Society. Used with permission.

Box 1 highlights one such network in Birmingham, UK.

However, despite the recent proliferation of UMNs, few cities are lucky enough to have an installation and even in those that do, the resolution of measurements remains insufficient for many applications. Furthermore, the experiences in setting up and maintaining UMNs has highlighted that they are time consuming, challenging in terms of data demands, and expensive to run (Chapman et al., 2015). Indeed, many existing city-scale networks have proved to be unsustainable in the long term, barely outliving the demonstration project stage.

For example, both the Oklahoma Micronet and METROS in Tokyo ran for just 3 years. Hence, this raises the question as to whether UMNs are actually the most sustainable way to achieve fine detail observations in our cities. The good news is that urban meteorological data is actually already available over the internet, from a variety of sources. The data is waiting to be harvested and used to further our scientific understanding of urban climates – if we are brave (and innovative) enough to exploit it.

Crowdsourcing & The Internet of Things

Non-standard data potentially provides urban meteorological data at an unprecedented scale. Such data is now being ubiquitously generated by a wide-range of sources (e.g. smart phones, vehicles, infrastructure, citizens, 'hidden networks') and there is much potential to 'crowdsource' this data to be utilised for the benefit of science and society. The difficulty is that such crowdsourced data is rarely quality assured / quality controlled which presently significantly limits its broader utility.

The term 'crowdsourcing' is become increasingly common; traditionally defined as 'obtaining data or information by enlisting the services of a large number of people', it now often refers to obtaining information from a range of public sensors, typically via the internet. Therefore a large amount of ubiquitous, real-time, high resolution data is now being routinely crowdsourced from a range of non-standard sources. Simultaneously, the 'Internet of Things' (IoT) – literally referring to any device (thing) with the capability to connect to the internet, is resulting in 'big' open datasets. Add to this ever-growing computational power, then our ability to harvest this data and improve our understanding of localised phenomenon at a high spatio-temporal resolution is unprecedented.

As a result, crowdsourcing is frequently used across a range of science disciplines (e.g. astronomy, ecology, zoology), yet despite the potential, the realisation of using crowdsourced data within atmospheric science disciplines remains in its relative infancy. This is particularly surprising given the highlighted paucity of weather stations in urban areas and indeed, the demand for high resolution climate data in our cities (Chapman et al., 2015), yet crowdsourcing has the potential to overcome these long standing issues related to spatial and temporal representativeness of weather observations.

There are a number of crowdsourcing techniques which can potentially be used and these can be classified as animate or inanimate, automated or manual, passive or active (see Muller et al., 2015 for a full review).

Citizen Science is collaborative research involving members of the public: volunteers, amateurs and enthusiasts. It can be thought of as a form of 'participatory sensing' actively involving citizens collecting or generating data. For example, the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS: http://www.cocorahs.org/) is a non-profit, community-based network of volunteers who measure and map precipitation using low-cost measurement tools.

Web 2.0: The recent proliferation of Web 2.0 channels (e.g. the Twitter micro-blogging site, Facebook social media site, picture sharing sites such as Flickr etc) have opened up opportunities to further engage with citizens for scientific purposes. Social media channels can now be used to harvest an array of geo-located, date and time-stamped information (e.g. data, notes, photos, videos), which can be accessed directly (e.g. using hash-tags or key words), and in real-time. For example, Muller (2013) used Twitter to map snow depths across the city of Birmingham.

In situ sensors: Whilst personal weather stations have been popular with amateur weather enthusiasts for decades, a new generation of internet-enabled low-cost instrumentation is now available for personal, research and operational use. Data contributes to the IoT and is transmitted by Wi-Fi, Bluetooth and machine-to-machine SIM cards. Repositories then harvest such data (e.g. the UK Met

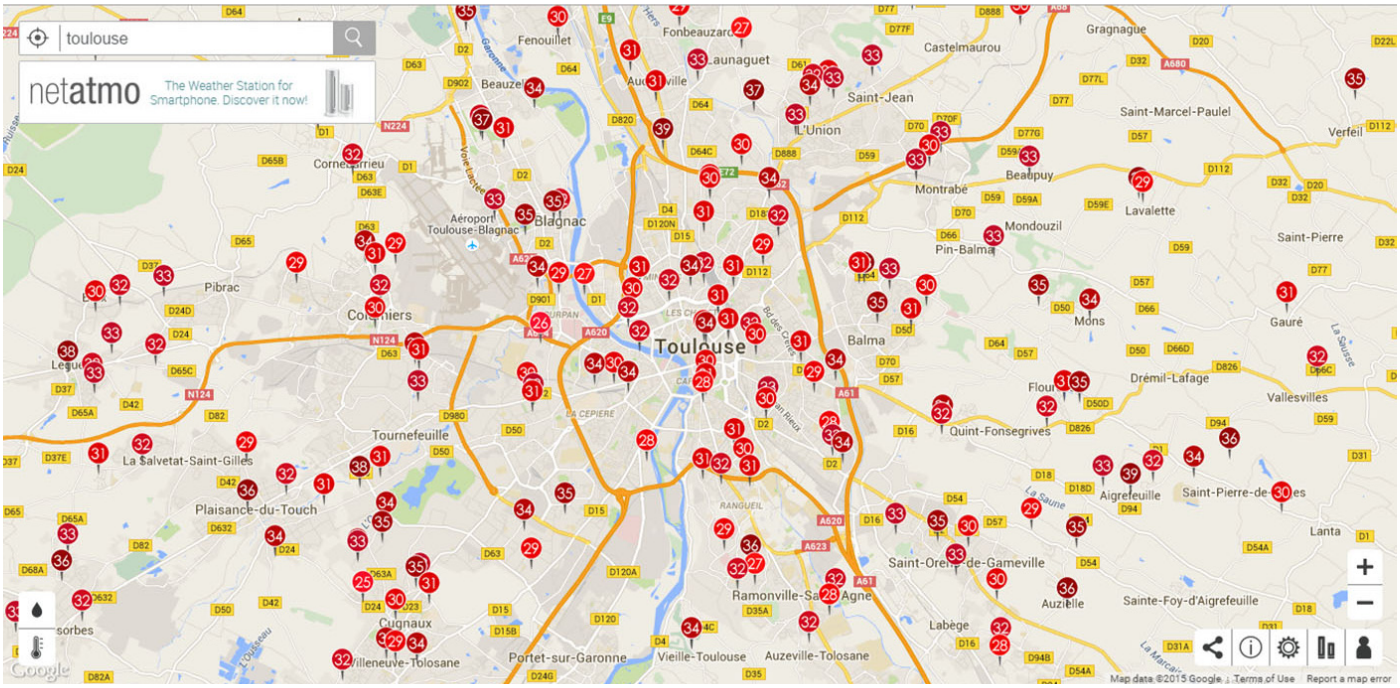


Figure 1. Sample air temperature data taken from NetAtmo weather stations across Toulouse.

Office 'Weather Observation Website' http://wow.metoffice.gov.uk and the NOAA Citizen Weather Observer Program (CWOP: http://wxqa.com/) (Bell et al., 2013).

Smart Devices: A large number of sensors are now being designed for connection to smart devices (e.g. EDN BlutolTemp Thermometer; Aginova iCelsius thermistor; Plus Plugg weather sensors and NetAtmo weather stations (Figure 1). Smartphones are a classic example of ubiquitous computing and a large number of apps are available to use the increasing in-built capability of GPS-enabled smartphones themselves. For example, Overeem et al (2013a) show the potential of using crowdsourced battery temperature from smartphones as an indicator of ambient air temperatures. Apps such as WeatherSignal act as hubs for such data, enabling users to acquire data in real-time (Figure 2).

Moving platforms: Many different types of platforms are used to conduct scientific research and collect data, so the use of moving platforms is far from a new concept. What is novel is the potential for any moving platform to routinely collect information. For example, Aeroflex, an air quality monitor equipped bicycle (Elen et al. (2012).

'Hidden' networks: Finally, it is important to highlight the potential for repurposing data from 'hidden' networks, as a form of inanimate, passive crowdsourcing. Numerous municipal networks exist, out of sight, quietly collecting routine data for various applications (e.g. mobile phone signals, sensors on lighting columns to control light levels, city-wide traffic sensors for transport management, in-built mobile sensors for monitoring the performance of the handset). However, these have the potential to be used as proxies for monitoring other variables. For example, Overeem et al. (2013b) used received signal level data from microwave links in cellular communication networks to monitor precipitation in the Netherlands.

Data Quality

Despite the abundance of the potential approaches highlighted, data quality concerns need to be addressed before the data becomes widely accepted in the atmospheric sciences; the absence of information on the accuracy and quality (QA/QC) of crowdsourced data is presently hindering it's utility. By definition, data are not typically acquired following 'best practices' in accordance to authoritative standards, and may come from a variety of sources of variable and unknown quality.

Hence, there needs to be a drive to investigate the potential of emerging crowdsourcing techniques. If the quality can be proven, this approach will ultimately yield sustainable high resolution data in any urban area at a fraction of the cost and effort, opening up new solutions to monitor climate prob-

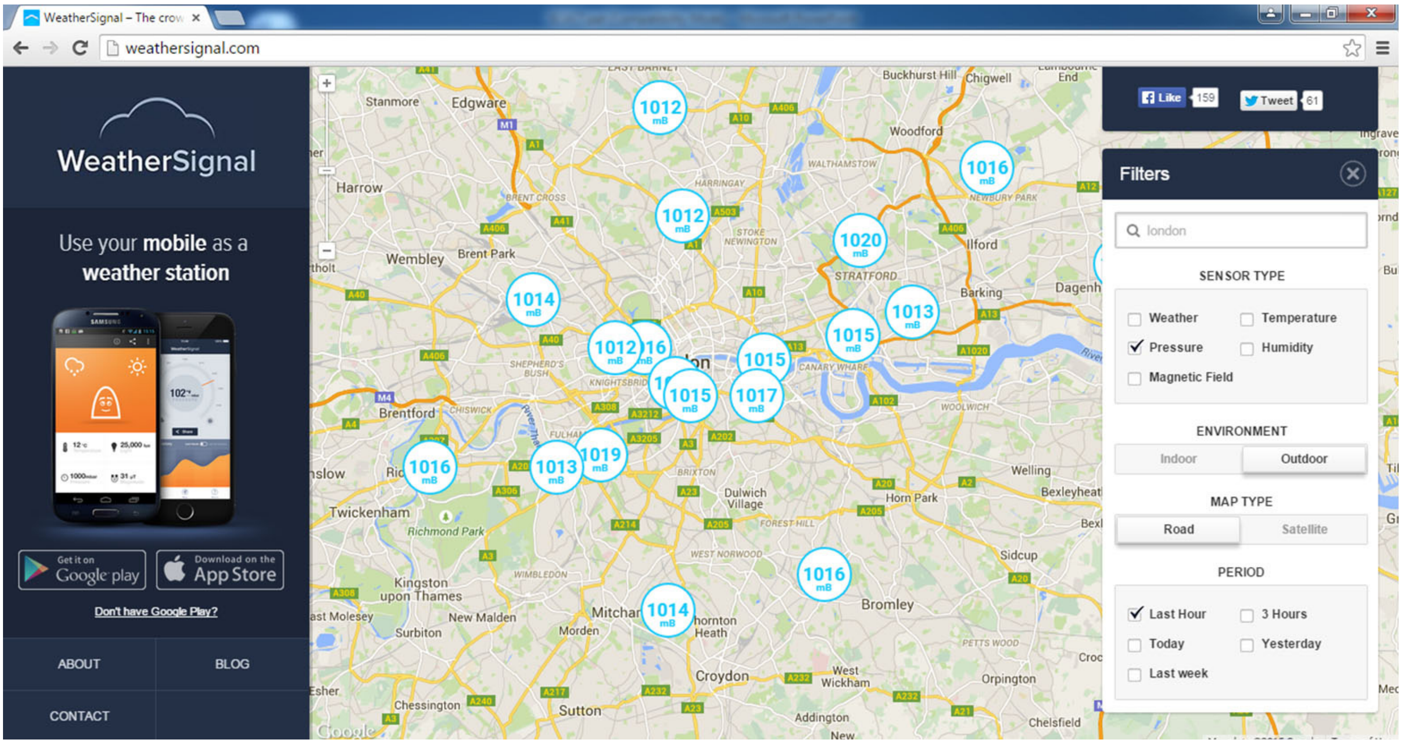


Figure 2. Sample atmospheric pressure across London taken from smartphones and accessed via the WeatherSignal website.

lems in cities. As such, the potential impact of using crowdsourced data would be transformative in urban climatology, allowing monitoring and modelling to be achieved on an unprecedented scale. However, achieving this presents a number of scientific challenges. Often it is assumed that more data leads to improved accuracy, as the erroneous outliers become more obvious (e.g. Foody et al., 2013; See et al., 2013). With these concerns in mind, a variety of methods are starting to emerge to assess the accuracy of crowdsourced data (Foody et al., 2014). Whilst this is quite a scientific challenge, comparisons with higher quality in-situ apparatus or other highly trusted 'gatekeepers' (i.e. calibrated and well maintained low cost devices) can greatly aid quality assurance by controlling biases (Goodchild and Li, 2012; Bell et al., 2015). It is here where existing UMNs can play an important role by providing the 'ground truth' measurements, thus becoming city-scale testbeds for new and emerging techniques.

Conclusion

There is clearly much work to be done before non-standard data sources such as those outlined are accepted by the atmospheric science community. Over a century of research into producing precise measurements cannot be ignored, but neither can the potential of complementing this existing dataset with new and exciting means to measure the urban climate at an unprecedented resolution. This approach does not signal the end of the deployment of UMNs across the world, but there is a need for researchers to step back and think about what is actually to be gained scientifically by instrumenting another city for a couple of years whilst funding permits. In summary, UMNs are too unsustainable to be an urban climatologist's panacea – instead, continued innovation and a willingness to consider new approaches is what is really needed to drive science forward.

References

Arnbjerg-Nielsen K, Willems P, Olsson J, Beecham S, Pathirana A, Bülow Gregersen I, Madsen H and Nguyen V-T-V. (2013) Impacts of climate change on rainfall extremes and urban drainage systems: a review, *Water Science and Technology*, 68: 16–28.

Bell S, Cornford D, Bastin L. (2013) The state of automated amateur weather observations. *Weather*, 68: 36-41.

Bell S, Cornford D, Bastin L. (2015) How good are citizen weather stations? Addressing a biased opinion. *Weather*, 70:75-84.

Beven L (2000) Uniqueness of place and process representations in hydrological modelling. *Hydrology and Earth Systems Science* 4:203-213.

Basara JB, Illston BG, Fiebrich CA, Browder PD, Morgan CR, McCombs A, Bostic JP, McPherson RA, Schroeder AJ, Crawford, KC. 2011. The Oklahoma city micronet. *Meteorological Applications* 18: 252-261.

Chapman L, Muller CL, Young DT, Warren EL, Grimmond CSB, Cai X-M, Ferranti EJS. (2015) The Birmingham Urban Climate Laboratory: An open meteorological testbed and challenges of the smart city. *Bulletin of the American Meteorological Society* 96:1545-1560.

Elen B, Peters J, Van Poppel M, Bleux N, Theunis J, Reggente M, and Standaert A. (2012) The Aeroflex: A Bicycle for Mobile Air Quality Measurements, *Sensors*, 13:221-240.

Foody GM, See L, Fritz S, Van der Velde M, Perger, C, Schill C, Boyd DS. (2013) Assessing the accuracy of volunteered geographic information arising from multiple contributors to an internet based collaborative project, *Transactions in GIS*,17: 847-860.

Foody GM, See L, Fritz S, Van der Velde M, Perger, C, Schill C, Boyd DS, Comber A. (2014) Accurate attribute mapping from volunteered geographic information: issues of volunteer quantity and quality, *The Cartographic Journal*, http://dx.doi.org/10.1179/1743277413Y.0000000070 1743277413Y.0000000070

Goodchild MF and Li L. (2012). Assuring the quality of volunteered geographic information, *Spatial Statistics*, 1:110-120.

Grimmond CSB, Roth M, Oke TR, Au YC, Best M, BettsR CG, Cleugh H, Dabbert W, Emmanuel R, Freitas E, Fortuniak K, Hanna S,Klein P, Kalkstein LS, Lui CH, Nickson A, Pearlmutter D, Sailor D, Voogt J. (2010) Climate and more sustainable cities: climate information for improved planning and management of cities (producers/capabilities perspective). *Procedia Environmental Sciences* 1: 247–274.

IPCC (2001) *Climate Change 2001: The Scientific Basis*. Cambridge University Press.

Koskinen JT, Poutiainen J, Schultz DM, Joffre S, Koistinen J, Saltikoff E, Gregow E, Turtiainen H, Dabberdt WF, Damski J, Eresmaa N, Goke S, Hyvarinen O, Jarvi L, Karppinen A, Kotro J, Kuitunen T, Kukkonen J, Kulmala M, Moisseev D, Nurmi P, Pohjola H, Pylkko P, Vesala T, Viisanen J. (2011) The Helsinki Testbed: A Mesoscale Measurement, Research and Service Platform. *Bulletin of the American Meteorological Society* 92: 325-342.

Muller CL. (2013) Mapping snow depth across the West Midlands using social media-generated data. *Weather*, 68: 82.

Muller CL, Chapman L, Grimmond, CSB, Young DT, Cai X. (2013) Sensors and the city: a review of urban meteorological networks. *International Journal of Climatology*, 33: 1585–1600.

Muller CL, Chapman L, Johnston S, Kidd C, Illingworth S, Foody G, Overeem A, Leigh RR. (2015) Crowdsourcing for Climate and Atmospheric Sciences: Current Status and Future Potential. *International Journal of Climatology* 35:3185–3203.

NRC (2010) www.nap.edu/openbook.php?record_id=12888 (accessed 25/11/2015).

Overeem A, Robinson JCR, Leijnse H, Steeneveld GJ, Horn BKP, Uijlenhoet R. (2013a) Crowdsourcing urban air temperatures from smartphone battery temperatures. *Geophysical Research Letters*, 40: 4081-4085.

Overeem A, Leijnse H, Uijlenhoet R. (2013b) Country-wide rainfall maps from cellular communication networks, *Proceedings of the National Academy of Sciences of the United States of America*, 110: 2741-2745.

See L, Comber A, Salk C, Fritz S, van der Velde M, Perger C, Schill C, McCallum I, Kraxner F, Obersteiner M. (2013) Comparing the Quality of Crowdsourced Data Contributed by Expert and Non-Experts, *PLoS ONE* 8(7): e69958. doi:10.1371/journal.pone.0069958.

Tomlinson CJ, Prieto-Lopez T, Bassett R, Chapman L, Cai XM, Thornes, JE, Baker CJ. (2013) Showcasing urban heat island work in Birmingham – measuring, monitoring, modelling and more, *Weather*, 68: 44049.

Young DT, Chapman L, Muller CL, Cai XM, Grimmond, CSB. (2014) A low-cost wireless temperature sensor: evaluation for use in environmental applications. *Journal of Atmospheric and Oceanic Technology* 31:938–944.

Calculation of the CO_2 storage term in an urban environment: Results and guidance from Central London

Introduction

Carbon dioxide is the greenhouse gas with the greatest effect on global warming (IPCC, 2014). Despite their (relatively) small areal extent (2%, Satterthwaite 2008), cities are the largest single source of CO_2 (Canadell et al., 2009). Monitoring of urban CO_2 emissions is therefore important in order to estimate global trends. Many previous studies have calculated urban CO_2 emissions from vertical flux measurements made at several times the height of local roughness elements (trees, buildings) and assumed that the amount of CO_2 stored below this measurement height was negligible. However studies in London (Helfter et al., 2011, Bjorkegren et al., 2015) show this not to be the case. CO_2 stored within the airspace below the EC measurement height can be significant.

Instruments to measure CO_2 concentrations at multiple heights, required for proper calculation of the CO_2 storage (see Bjorkegren et al., 2015 for details), are expensive and may be impossible in urban areas. Vertical CO_2 concentration (*[CO_2]*) profiles in Basel, Switzerland (Lietzke and Vogt, 2013) and London, UK (Bjorkegren et al., 2015) show important differences from their rural counterparts. Given the calculated change in CO_2 stored (ΔC_S) within the airspace depends upon the shape and variation of the CO_2 profile; this suggests that recommendations developed for measurement of ΔC_S within rural areas may not be applicable to urban areas. This study addresses that problem by examining the spatial density and temporal resolution of *[CO_2]* measurements required to quantify the storage term, and testing of the effect of different interpolation methods on the collected data. A method of assessing the quality of calculated ΔC_S data is proposed.

Site and Measurements

Data were collected in central London at the King's College London, Strand Campus (KS) (Figure 1a, b, c). Site details, collection methods and data processing are described in Bjorkegren et al. (2015). In brief, *[CO_2]* data

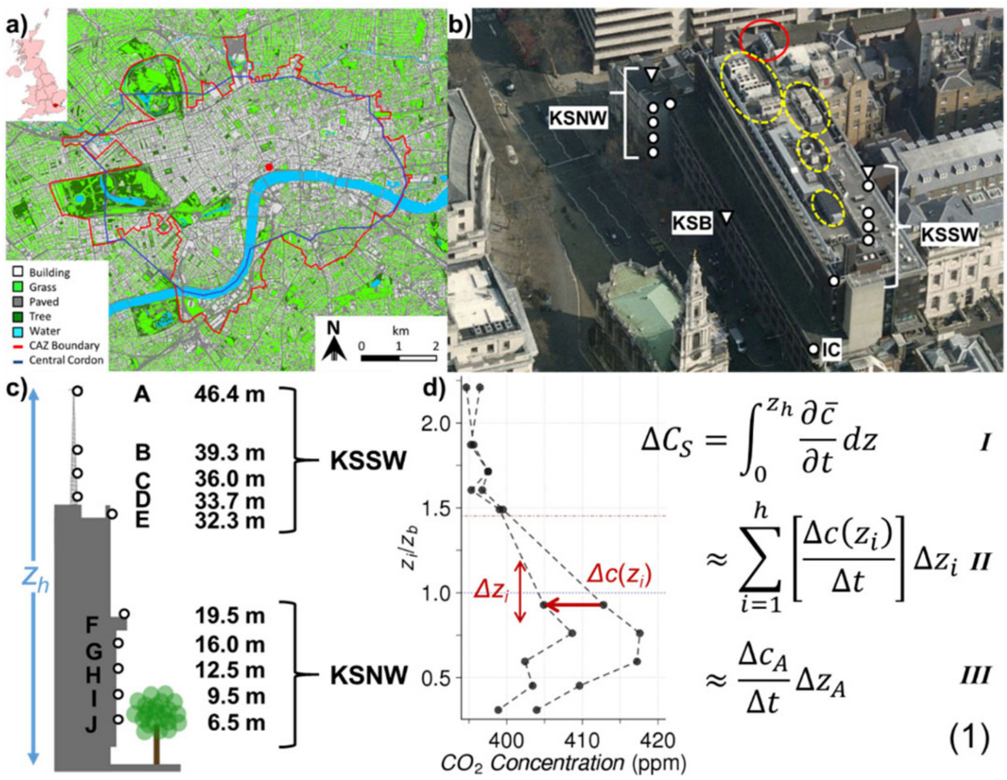


Figure 1. Measurement locations at King's College London, Strand Campus (KS), London, UK, some example results and the method of calculating CO_2 storage. (a) Land cover map (Lindberg and Grimmond, 2011) centred on the KS (red dot) with the Central Activity Zone (CAZ, red line), Transport for London (TfL) Central London Cordon (blue line) and position of London within the UK (inset). (b) Sample sites at KS including switched *[CO_2]* profile (white circles: KSSW, KSNW and inter comparison point, IC) and EC (inverted white triangles). Rooftop sources are circled: chillers (yellow, dotted), boiler chimneys (red, solid). (c) Vertical *[CO_2]* profile locations, z_i, viewed from the road adjacent to KSNW in (b) with height above ground level. (d) CO_2 concentrations collected at the heights in (c) on the 9th June, 2012 at (right) 10:45 and (left) 10:55 GMT. Equation (1) relates the theoretical calculation of CO_2 storage (I) to the calculation from a vertical profile of measurements (II) and from data collected at a single height, Z_h (III). Image in (b) taken in October, 2011, during the leaf off period (Microsoft, 2011). This is a modified version of Fig. 1 in Bjorkegren et al. (2015).

were collected at 10 heights (heights A to J, Figure 1c) for 75 s at each height by two LI840 closed path infrared gas analysers (circles, Figure 1b). CO_2 concentration data were also collected at heights A and F by two LI7500 open path IRGAs (triangles, Figure 1b). The LI7500s had common sampling points with one sample location of each LI840, and the two LI840s were inter-compared by a common sample point at IC (Figure 1b).

CO_2 storage was calculated from both the vertical profile (ΔC_{SP}, term II in Eq. 1 – see Fig. 1) and measurements made at height A only (ΔC_{SS}, term III in Eqn 1). In this study the former is referred to as the profile method and the latter as the single height method. For more detail on the derivation, please see Finnigan (2006) and Bjorkegren et al. (2015).

Spatial Density

When planning the position of sampling points the aim is to characterise the vertical *[CO_2]* distribution using measurements at as few locations as possible. This minimises data loss if measurements are made by selecting airstreams from each location using a valve array, and reduces instrumentation, installation and running costs. Measurements need to be closer together where the *[CO_2]* changes rapidly with height. For rural profiles this is close to ground level as the major source of CO_2 is sub-surface respiration (e.g., Wofsy et al., 1993; Jarvis et al., 1997; Iwata et al., 2005; Araujo et al., 2010). Urban vertical profiles reported by Bjorkegren et al. (2015) suggest that CO_2 concentrations are relatively homogenous between the street and the roof level, and also directly above roof level to the top of the roughness sub-layer, but that there is a sharp difference between the two with a transition zone at roof level. This suggests that the vertical CO_2 profile could be adequately measured by one sample point within the canyon and one above.

This is tested following Yang et al. (2007). A ΔC_S time series calculated from all available sample inlets is defined as 'best practice' (ΔC_{SBP}) and CO_2 storage time series calculated from other configurations are assessed based on the agreement with ΔC_{SBP}, with the configurations with the lowest and highest root mean squared error considered the best and worst configurations in each group respectively. All configurations included height A, as a measurement point located at several times the height of the local roughness elements is required for the eddy covariance measurements used to calculate vertical CO_2 fluxes. Configurations are assigned to groups based on the number of sample locations included in the ΔC_S calculation, i.e., 'Group 5' consists of all configurations with five sample locations. For details of the ΔC_S calculation, see Bjorkegren et al. (2015).

The best results for all groups are obtained when the distance between inlet heights is maximised, in other words, when samples are spread as evenly across the vertical extent of the volume of interest as possible. The coefficient of determination (R^2) for the best configuration in group 2 (heights A and F) is 0.85, up from 0.15 for group 1 (height A only) and a little lower than that for group 3 (0.95, heights A, F and J). Hence two to three sample points, if appropriately placed (spread equally across the span of the vertical profile) are found to be sufficient to measure ΔC_S in an urban area.

Temporal Density

The two main controls on the temporal resolution of measurements are the sensor response time and the sensor sampling interval. The effects of these are tested by smoothing (using a modified, single sided cosine function) and subsampling high (20 Hz) CO_2 concentration time series (2013/013 to 2013/043) then comparing the calculated ΔC_S values. LI840 data measured at the same locations as the LI7500s (continuous, 2 Hz) are also subsampled at intervals up to ten minutes to check that the results were not sensor-specific.

Due to the volume of data, computationally it is too expensive to plot the instantaneous values. Instead the total change in stored CO_2 is calculated as the sum of the instantaneous values for each half hourly period. The ratio of the effective height (z') to the Obukhov length (L) (for details, see Bjorkegren et al., 2015) is taken as a measure of atmospheric stability for each 30 minute period. There is some indication that ΔC_S values vary with stability, with the lowest values observed under neutral conditions, but this is not found consistently across all time resolutions.

The effect of the sensor response time on calculated ΔC_S is greatest between 0.1 and 5 s (Figure 2), (10 to 0.2 Hz). Decreasing the smoothing length below 0.1 s does not seem to affect calculated ΔC_S, indicating an instrument response time of 0.1 s is sufficient. Little change was found with increasing response time above 1 s.

Interpolation in Space and Time

In theory the CO_2 storage calculation requires *[CO_2]* measurements that are continuous in time and space (Figure 1, Eqn 1; Aubinet et al., 2005). However, as *[CO_2]* measurements are often made by sampling from several specific heights sequentially (Molder et al., 2000), the resulting data are discontinuous in both time and space. Prior to calculation of ΔC_S the 'missing' data at each measurement height can be interpolated in time to provide a continuous *[CO_2]* time series from which complete profiles can be drawn. Alternatively, measurements made at one location for a short time period, e.g. 75 s, may be considered representative for the entire period e.g., 10 minutes, during which the system cycles through all the measurement locations.

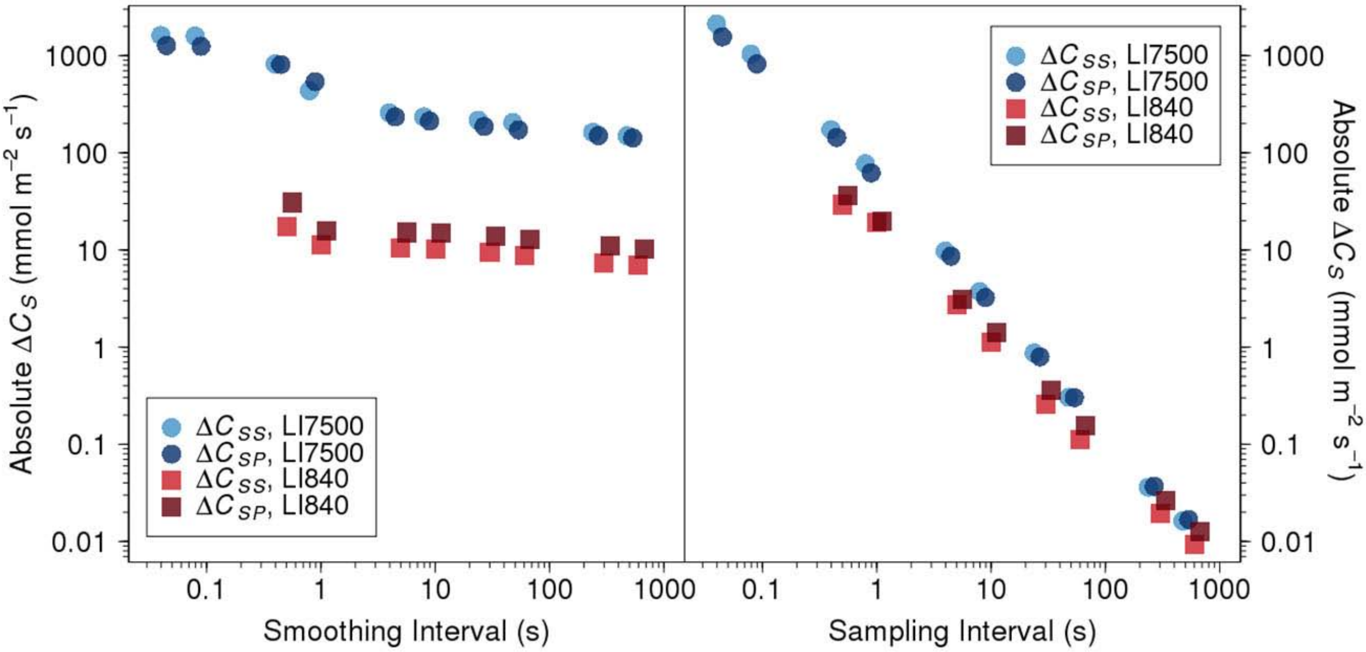


Figure 2. Median absolute value of half hourly summed CO_2 storage (ΔC_S) calculated with (left) smoothing and (right) subsampling of the CO_2 concentration time series collected by LI7500 (20 Hz, circular points, see key) and LI840 (2Hz, square points) continuously at KSSW and KSNW (Heights A and F, Figure 1c) for 2014/013-2014/043. ΔC_{SS} (darker shading) calculated from data collected from height A only; ΔC_{SP} (lighter shading) from data collected at heights A and F. The degree of smoothing and subsampling ranges from none (i.e., raw 20 Hz or 2 Hz data) to 600 s.

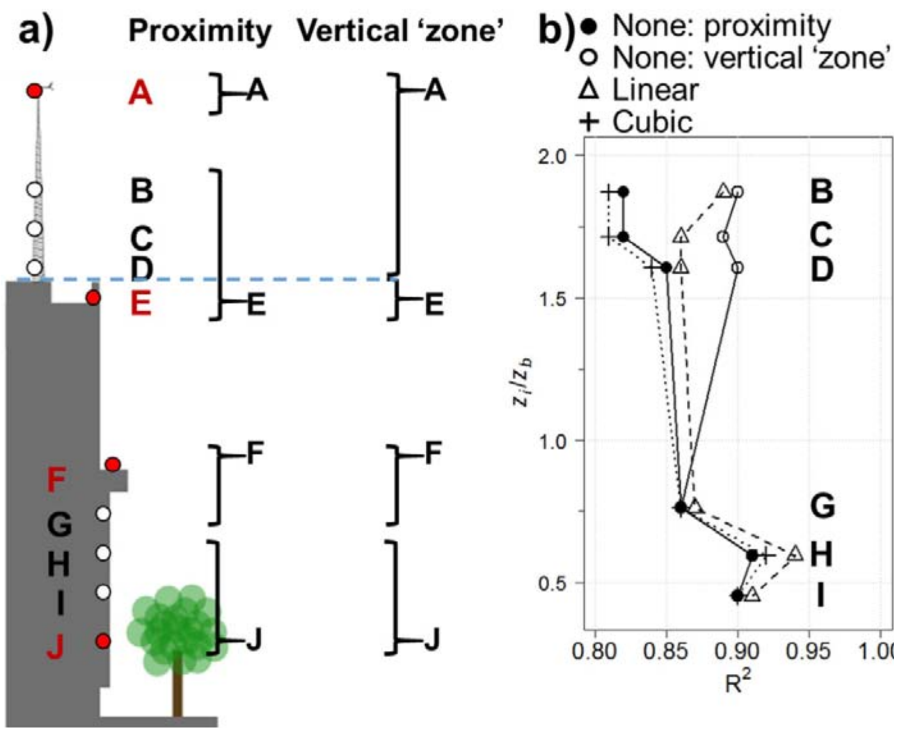


Figure 3. (a) Locations of the extracted (red, filled points) and interpolated (hollow points) *[CO_2]* time series relative to the KS building. Proximity and vertical zone interpolation are illustrated by grouping interpolated heights under a bracket labelled with the relevant extracted heights. (b) Coefficient of determination (R^2) for a regression of the interpolated *[CO_2]* time series at measurement points B, C, D, G, H and I onto the measured values for four interpolation methods (key: above plot).

The second stage in the ΔC_S calculation is to integrate the change in *[CO_2]* with time over the vertical extent of the volume of air of interest (Aubinet et al., 2005). One way is to multiply the change in *[CO_2]* with time at each measurement height by the vertical distance over which the measurement is considered to be representative; this is known as 'span weighting' the measurement. Another method is to interpolate to values to a metre grid and sum over the height of the air volume.

Continuous 2 Hz LI840 *[CO_2]* measurements (KSSW, z_i = 46.4 m, 2013/160 – 365) are used to assess the effectiveness of different methods of interpolating *[CO_2]* in time. A benchmark time series of 8 data points per ten minutes is generated by processing the data as described in Bjorkegren et al. (2015). Every 8th data point is extracted (simulating the data gaps of a system that samples multiple locations consecutively) and used as input data for three different interpolation functions. The first is 'constant' or 'no' interpolation which gap fills with the measured value. The second and third methods are 'linear' and 'cubic' spline interpolation using the *approx* and *spline* R functions (R Core Team, 2013) respectively with no interpolation of leading or trailing missing values.

Regression of the interpolated *[CO_2]* time series on to the benchmark gave $R^2 > 0.98$ for all methods, with linear interpolation giving the highest R^2 and lowest RMSE, but the 'constant' or 'no' interpolation giving values for the regression slope and intercept closer to 1.0 and 0.0 respectively. Cubic interpolation of *[CO_2]* is the least effective method by a small margin.

The results do not support interpolation of ΔC_S as none of the R^2 values exceed 0.05. Despite this, regression of ΔC_S calculated from the linearly interpolated time series on to the benchmark has a slope and intercept of 0.95 and 0.00 respectively. The linear interpolation also has the lowest RMSE. The low correlation between interpolated and benchmark ΔC_S, as well as the high error in interpolated *[CO_2]* relative to typical ΔCS values (~ 1 μmol m-2 s-1) support using systems with fewer, continuous measurements rather than switching between multiple locations.

The effectiveness of interpolating *[CO_2]* in space is evaluated by extracting *[CO_2]* time series at four heights (A, E, F, J, Figure 3) and interpolating to the remaining six (B, C, D, G, H, I). As before, the interpolation methods are: none (i.e., *[CO_2]* at the interpolated heights is considered to be the same as *[CO_2]* at the extracted heights), linear, and cubic. For the 'none' method, CO_2 concentrations are either assumed to be equal to those at the closest extracted height ('proximity', Figure 3a), or to the closest extracted height within the portion of the vertical profile that has the same physical characteristics, i.e., below or above roof level (vertical 'zone', Figure 3a).

Linear interpolation gives the lowest RMSE when summed over all time series at all interpolated heights, followed by 'none' and cubic (51.7, 58.3, 58.6 ppm, respectively). Linear interpolation performs best below roof height and 'none' (vertical 'zone', Figure 3b) is more effective above. Regression of interpolated on benchmark ΔC_S for all methods gives $R^2 > 0.8$ at all heights (Figure 3b) and could be applied without prior knowledge of the vertical *[CO_2]* distribution. If the typical *[CO_2]* behaviour at a site is known and there are obvious physically induced transition points between different 'zones' e.g. above vs. below canopy height, weighting of the change in *[CO_2]* with time by the distance between the transition points and not to the midpoints between sample locations ('none: vertical zone') reduces the interpolation error.

Quality assessment

CO_2 concentration data for this section were collected at 10 Hz by LI7500 at heights A and F (Figure 1c). The period 2013/347 – 2013/365 was chosen for analysis despite the higher chance of adverse weather affecting the open path sensor as the university was closed, reducing rooftop emissions from fuel combustion for space heating, and stable atmospheric conditions (where ΔC_S is expected to be relatively large) were more likely (see supplementary material of Bjorkegren et al., 2015).

Wavelet analysis was performed on data sets of 30 minutes. For details of the wavelet analysis method and its advantages relative to other spectral density estimation methods, see Bjorkegren et al. (2015). In brief, the Mexican hat wavelet was applied at 53 temporal scales between 0.2 s and 27.3 minutes following the method of Torrance and Compo (1998). The results were summed over time to give the global wavelet spectra (equivalent, after normalisation, to the standard energy spectra calculated by Fourier transform) and binned by frequency or timescale and atmospheric stability class for each half hourly data set (z'/L, height A, KSSW).

Linear relations on a log-log axis, i.e., power law relations with frequency are found for ΔC_S calculated using both the profile (ΔC_{SP}) and single-height (ΔC_{SS}) methods. These include a roughly 1:1 relation for power spectral density and frequency for 0.005 to 0.1 Hz (200 to 10 s), and an almost 1:2 relation for 0.1 to 0.5 Hz (10 to 2 s) (Figure 4a). Peak spectral energy for spectra normalised by the natural frequency is found between 0.001 and 0.004 Hz (8 to 16 minutes) and a smaller secondary peak is observed at 0.1 Hz (10 s). At frequencies below 0.1 Hz spectral power decreases as an inverse-power law (exponent of approximately −2/3) under all stability conditions. A similar relation between spectral power and frequency was observed in power spectra of *[CO_2]* measurements in rural areas (e.g. Goulden et al., 1996) and suggests

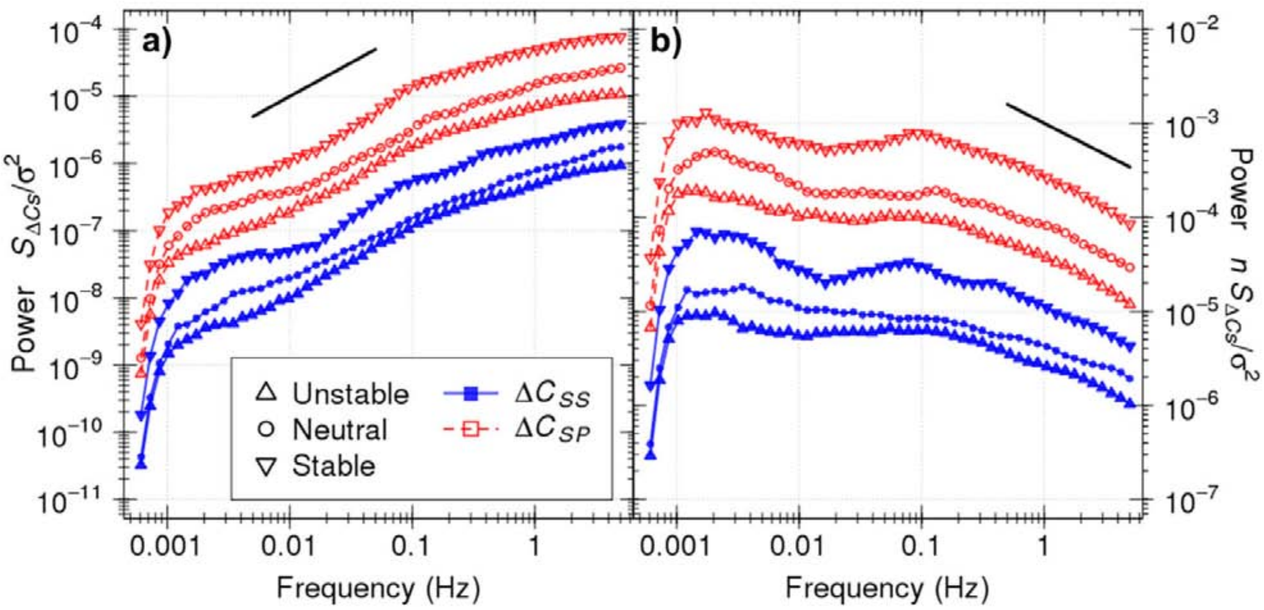


Figure 4. Global wavelet power spectra (S) normalised by (a) the variance (σ^2) plotted with frequency in Hz by stability class (key) for CO_2 storage calculated from data at a single location (ΔC_{SS}) and CO_2 storage from profile measurements (ΔC_{SP}); (b) as (a) but normalised by natural frequency (number of cycles, n, in 30 minutes). The solid black line in each subfigure indicates a power-law exponent: (a): 1.00, (b): -0.667. Note each y-axes has a different scale. ΔC_{SS} was calculated from 10 Hz LI7500 data measured at height A (Figure 1c), ΔC_{SP} from 10 Hz LI7500 data measured at heights A and F (Figure 1c), 2013/347 – 2013/365. Stability classes correspond to z'/L (effective height z' over the Obukhov length L) ranges as follows: unstable: -1000 < z'/L ≤ -0.01, neutral: -0.01 < z'/L ≤ 0.01, stable: 0.01 < z'/L ≤ 1000.

that, as with *[CO_2]*, inspection of power spectra could be used to assess the quality of calculated CO_2 storage. However, further research and results from a greater variety of sites are needed.

Conclusions

The typical urban vertical CO_2 concentration distribution shows significant differences from rural ones. This affects the number of sample points required to measure CO_2 stored within the airspace. Unlike in rural areas, where multiple measurements close to the ground are needed, results presented here suggest that in urban areas only one measurement within the street canyon is required in addition to those at the height of the eddy covariance equipment. The procedure for calculating the CO_2 stored within an airspace depends on whether the typical vertical distribution of CO_2 is known. If it is known, the change in *[CO_2]* with time at each measurement height should be weighted by the vertical span over which the CO_2 concentrations behave similarly to those observed at the measurement point. Otherwise, changes in CO_2 concentration with time should be interpolated linearly between measurement heights. If possible, CO_2 concentrations should be measured continuously in time with a sensor response time better than 0.1 s. The absolute magnitude of CO_2 storage declines with sampling frequency and CO_2 storage potentially has a power law relation to frequency, but we welcome results from other sites to investigate this further.

References

Araujo, A. C., Dolman, A. J., Waterloo, M. J., Gash, J. H. C., Kruijt, B., Zanchi, F.B., de Lange, J.M.E., Stoevelaar, R., Manzi, A.O., Nobre, A.D., Lootens, R.N., Backer, J. (2010) The spatial variability of CO2 storage and the interpretation of eddy covariance fluxes in central Amazonia. *Agricultural and Forest Meteorology* 150, 226 – 237

Aubinet, M., Berbigier, P., Bernhofer, Ch., Cescatti, A., Feigenwinter, C., Granier, A., Grünwald, Th., Havrankova, K., Heinesch, B., Longdoz, B., Marcolla, B., Montagnani, L., Sedlak, P. (2005) Comparing CO_2 storage and advection conditions at night at different Carboeuroflux sites. *Boundary-Layer Meteorology* 116, 63-93

Bjorkegren, A.B., Grimmond, C.S.B., Kotthaus, S., Malamud, B.D. (2015). CO2 emission estimation in the urban environment: Measurement of the CO2 storage term. *Atmospheric Environment*, 122, 775-790

Canadell, J.G., Ciais P., Dhakal S., Le Quéré C., Patwardhan A., Raupach M.R. (2009) The global carbon cycle 2 - the human perturbation of the carbon cycle. Paris, France: UNESCO-SCOPE-UNEP Policy Briefs, No. 10

Finnigan, J. (2006) The storage term in eddy flux calculations. *Agricultural and Forest Meteorology*, 136, 108-113

Goulden, M. L., Munger, J. W., Fan, S. -M., Daube, B. C., Wofsy, S. C. (1996) Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. *Global Change Biology*, 2, 169-182

Helfter, C., Famulari, D., Phillips, G. J., Barlow, J. F., Wood, C., Grimmond, C. S. B. and Nemitz, E. (2011) Controls of carbon dioxide concentrations and fluxes above central London. *Atmospheric Chemistry and Physics*, 11(5), 1913-1928

Hutyra, L. R., Munger, J. W., Hammond Pyle, E., Saleska, S. R., Restrepo-Coupe, Daube, B. C., de Camargo, P. B., Wofsy, S. C. (2008) Resolving systematic errors in estimates of net ecosystem exchange of CO_2 and ecosystem respiration in a tropical forest biome. *Agricultural and Forest Meteorology*, 148, 1266-1279

Iwata, H., Yadvinder, M., van Randow, C. (2005) Gap-filling measurements of carbon dioxide storage in tropical rainforest canopy airspace. *Agricultural and Forest Meteorology*, 132, 305-314

Jarvis, P. G., Massheder, J. M., Hale, S. E., Moncrieff, J. B., Rayment, M., Scott, S. L. (1997) Seasonal variation of carbon dioxide, water vapour, and energy exchanges of a boreal black spruce forest. *Journal of Geophysical Research: Atmospheres*, 102(D24), 28953-28966

Lietzke, B., & Vogt, R. (2013). Variability of CO_2 concentrations and fluxes in and above an urban street canyon. *Atmospheric Environment*, 74, 60-72

Lindberg, F., Grimmond, C. S. B. (2011) Nature of vegetation and building morphology characteristics across a city: Influence on shadow patterns and mean radiant temperatures in London. *Urban Ecosystems*, 14, 617-634

Microsoft, Simmons (2011) Strand Campus, King's College London, UK. 51.511946, -0.116481. [Online] https://www.bing.com/maps/#Y3A9NTIuMjE3NDk5fjAuMTcxNzAwJmx2bD02JnN0eT1yJmVvPTAmcT1XQzJSJTIwMkxT [Accessed online 14 Sep. 2015]

Mölder, M., Lindroth, A., Halldin, S. (2000) Water vapour, CO2, and temperature profiles in and above a forest—accuracy assessment of an unattended measurement system. *Journal of Atmospheric and Oceanic Technology*, 17, 417–425

R Development Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Salmond, J.A., Oke, T.R., Grimmond, C.S.B., Roberts, S., Offerle, B. (2005) Venting of heat and carbon dioxide from urban canyons at night. *Journal of Applied Meteorology*, 44, 1180-1194

Satterthwaite, D. (2008) Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environment and Urbanization*, 20 (2), 539-549

Torrance, C., Compo, G.P. (1998) A practical guide to wavelet analysis. *Bulletin of The American Meteorological Society*, 79(1), 61-78

Wofsy, S. C., Goulden, M. L., Munger, J. W., Fan, S. –M., Bakwin, P. S., Daube, B. C., Bassow, S. L., Bazzazz, F. A. (1993) Net exchange of CO_2 in a mid-latitude forest. *Science*, 260 (5112), 1314-1317

Yang, B., Hanson, P. J., Riggs, J. S., Pallardy, S. G., Heuer, M., Hosman, K. P., Meyers, T. P., Wullschleger, S. D., Gu, L.-H. (2007) Biases of CO_2 storage in eddy flux measurements in a forest pertinent to vertical configurations of a profile system and CO_2 density averaging. *Journal of Geophysical Research*, 112, D20

Alex Bjorkegren

bjorkegren.a@gmail.com

King's College London, UK

Sue Grimmond

University of Reading, UK

This project was possible due to funding to Grimmond as part of the NERC grant NE/H003231/1 ClearfLo project, EU emBRACE (282672), EU BRIDGE (211345) and co-finance by "HORIZON 2020" EU Framework Programme (UrbanFluxes). For a full list of those who contributed to the work, see Bjorkegren et al. (2015).

Large-eddy simulations to characterize the role of turbulent and dispersive production, transport and dissipation of TKE over and within a realistic urban canopy

Abstract – A characterization of the vertical structure of turbulent kinetic energy (TKE) and of its budget terms over a realistic urban geometry in the city of Basel, Switzerland, is here performed via large-eddy simulation. We consider fully developed flow over a 512x512m subset of the city, centered at a location where extensive tower-measurements are available from the Basel Urban Boundary Layer Experiment (2001-02). In agreement to measurements, TKE in the roughness sublayer (RSL) is found to be primarily produced at roof-level. Here, turbulent production overcomes dissipation by SGS stresses and the excess in TKE is dislocated down into the cavities of the urban canopy layer (UCL), and upwards into higher parts of the RSL by turbulent transport and dispersive transport terms. Turbulent and dispersive transport terms are comparable in magnitude and act as a sink of TKE in the upper RSL and as a source term in the lower RSL and UCL. The spatial heterogeneity of mean velocities and Reynolds stresses in the lower RSL and in the UCL results in a significant wake production rate of TKE. Moreover, pressure transport is found to be a significant source of TKE in the lower UCL, whereas transport by SGS stresses is negligible throughout the RSL.

Introduction

Accurate modeling of flow and turbulence in the urban roughness sublayer (RSL) is essential to properly predict weather, air quality, and dispersion of gases in urban environments. Within the RSL flow and turbulence exhibit strong spatial variations in both the vertical and the horizontal directions and hence Monin-Obukhov similarity (MOST) is not applicable. Nevertheless, one dimensional urban canopy parameterizations (UCPs), used to represent the effects of urban surfaces in mesoscale weather forecasting and air pollution dispersion models, are still relying on MOST relationships to compute vertical fluxes of momentum and scalars such as heat, humidity or pollutants between the urban facets and the atmosphere. Proper techniques to reintroduce a 1D approach in a truly three-dimensional RSL should account for the inherently variable canopy morphology, and its hierarchical structure of scales, as discussed in Britter and Hanna (2003). The increased availability of high resolution digital datasets on urban morphology is recently promoting the use of real topographies in CFD studies (see for instance Kanda et al., 2013). Further, advances in computational power now allow for representation of the three-dimensional processes of interest at the neighborhood scale. Output from numerical models, such as large-eddy simulations (LES), can therefore be used to understand the physics of the flow and quantify the most relevant terms and processes that occur in realistic urban RSLs. This is the goal of the current study, where LES are used to resolve the airflow over and within a detailed urban geometry and to characterize the vertical structure of the turbulent kinetic energy (TKE) and the role of TKE budget terms in the RSL. Such information can then guide and/or validate approaches used in one-dimensional UCPs.

Throughout the study H will denote the top of the boundary layer, a given height in the domain will be denoted as z_{label}, where the subscript "label" will refer to various specific heights. Further, $\tilde{(\cdot)}$ is used to denote a spatially filtered variable (the spatial filtering that is implicitly understood in LES), $\overline{(\cdot)}$ denotes time-averaging, $\langle\cdot\rangle$ denotes horizontal (x, y) intrinsic averaging (fluid domain only), time fluctuations are written as $(\cdot)'$ and departures of time-averaged terms with respect to their horizontal mean are denoted as $(\cdot)''$. We will use $(\cdot)^*$ to denote a normalized variable.

Numerical algorithm and setup of simulations

The isothermal filtered Navier-Stokes equations are solved on a 512 × 512 × 160 m regular domain, where a subset of the city of Basel, Switzerland is used as lower interface (see Fig. 1). The LES algorithm was developed in Albertson and Parlange (1999) whereas the immersed boundary method (IBM) algorithm is a minor modification of Chester et al. (2007). Equations are solved on a regular domain $L_x \times L_y \times H$, imposing a free-lid boundary condition at $z = H$, using the IBM algorithm to account for the lower interface, and where periodic boundary conditions are applied in the horizontal directions. The flow is forced through an imposed pressure gradient, resulting in a friction velocity $u_* \approx 1$ m s^{-1} (fully rough regime). Two hydrodynamic roughness lengths, $z_0 = 0.15$ and $z_0 = 0.3$, and two LES closure models are considered: the classical static Smagorinsky model (Smagorinsky, 1963), and the scale-dependent model with Lagrangian averaging of the coefficient (LASD) (Bou-Zeid et al., 2005).

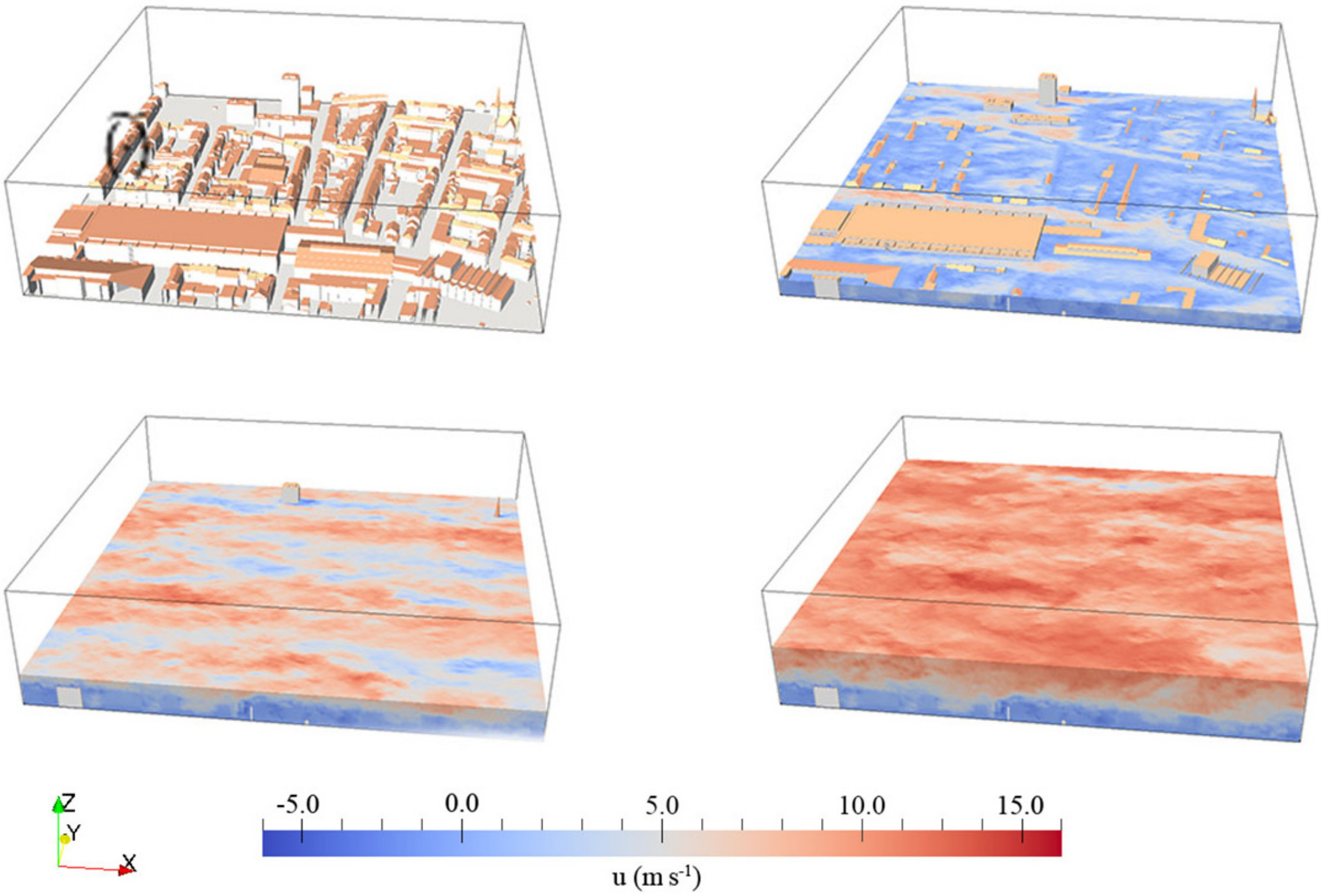


Figure 1. Reference surface and color contour of the dimensional stream-wise wind velocity at the planes $z/z_h = 1$, $z/z_h = 2$, $z/z_h = 4$ for the across-canyon wind direction (SMAG model, $z_0 = 0.15$).

During BUBBLE, a 32 m high tower was deployed inside the 13 m wide Sperrstrasse street canyon in Basel, Switzerland (Rotach et al., 2005). The computational domain is centered at the tower location where wind components u, v, w and virtual acoustic temperature θ were continuously recorded at six levels. The orientation of the street canyon is along the axis 066º - 246º (ENE to WSW). Data acquisition systems and quality control procedures including wind-tunnel calibrations of the instruments are described and documented in Christen (2005). We consider two directions of the incoming wind, α = 66º and α = 156º, which correspond to an along-canyon (Sperrstrasse) and an across-canyon wind regime. Equations are integrated in time for 480 non-dimensional time units $T = z_h/u_\tau$ (≈ 2 hours in dimensional time) in the coarser grid, before being used as initial condition for the finer grid, where they are further integrated for 250T.

Results and discussion

A color contour of the stream-wise velocity field for wind approaching from SSE (across-canyon regime) is displayed in Fig. 1. The flow is characterized by a broad spectrum of explicitly resolved length scales, as typical of LES approaches, which are heterogeneous in space and strongly depend on the actual configuration of the buildings. Double averaged (DA) numerical profiles are made dimensionless using the friction velocity and the mean building height (z_h = 15.3 m) as repeating variables. Tower profiles are first rescaled with the ratio between measured and simulated quantity at the tower top location and then normalized as DA profiles. Throughout the study z_γ will denote the height where the stream-wise velocity profile shows an inflection point. Normalized profiles of TKE and wake kinetic energy (WKE) are shown in Fig. 2. Locally sampled time-averaged LES data show relatively good agreement with measured data for both wind directions. LES slightly under-predicts TKE in the urban canopy layer (UCL), when compared against measured values. This might be partly due to boundary conditions we could not include in the model, or to lack of resolution in these delicate regions of the flow. TKE peaks at z_γ for the across-canyon wind regime and slightly above z_γ in the along-canyon wind regime, to then decrease linearly with height, consistent with tower measurements for the across-canyon wind regime and

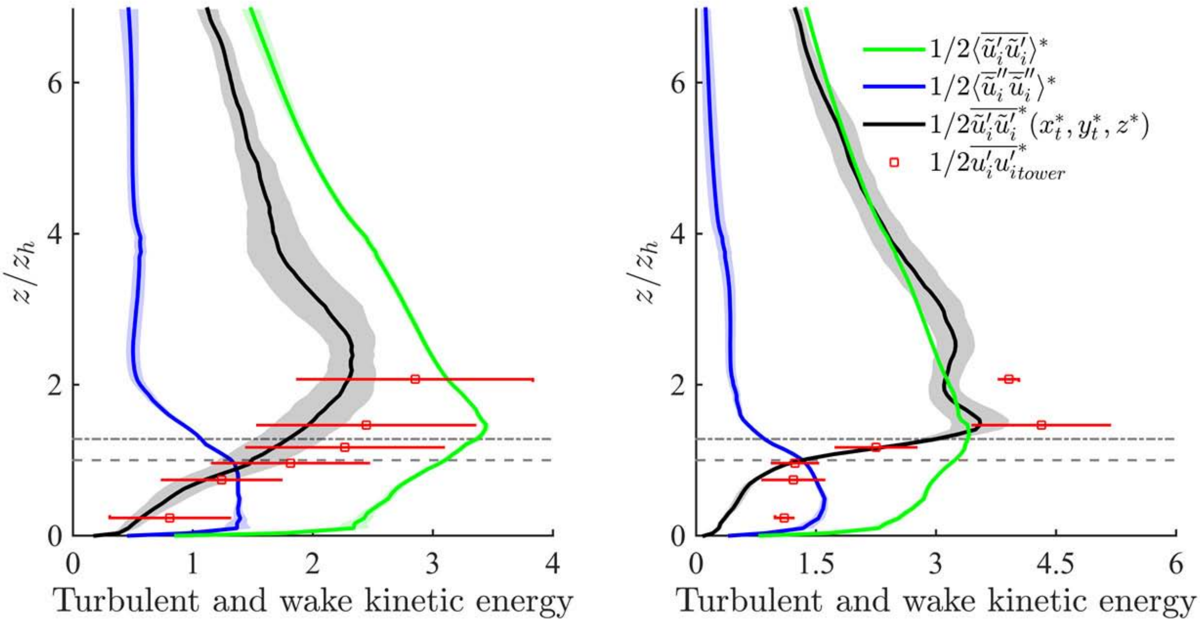


Figure 2. Comparison of TKE and WKE against tower-measured data for wind approaching from ENE (top) and SSE (bottom). Notation: DA TKE, green; dispersive TKE, blue; time-averaged locally-sampled TKE, black; tower data, red circles. Horizontal dashed and dot-dashed (grey) lines denote z_h and z_γ respectively.

in agreement with results from flow over random height cubes (Xie et al., 2008). A peculiar feature of the current study is the remarkable strength of TKE in the UCL, when compared against results from flow over gravel beds (Mignot et al., 2009) or flow over regular/random arrays of cubes (Coceal et al., 2006; Xie et al., 2008). This might be induced by the presence of organized street canyons, which allow the flow to develop significant MKE that then cascades into WKE and TKE due to surface drag and due to the energy cascade process. Further, for both wind directions, WKE is approximately constant within the UCL and shows a rapid decay in the lower RSL. The relatively large WKE in the RSL for the along-canyon wind regime is due to locking of streaks in between high-rise structures in the RSL. From Fig. 3 it is apparent that, for both approaching wind angles, DA turbulent shear production $\langle P_s \rangle$ peaks exactly at the inflection point $z_\gamma = 1.28z_h$. This location is connected with the presence of thin shear layers that separate from the highest buildings, and are advected downstream. A second maximum is found in the $\langle P_s \rangle$ profile, which can be regarded as a very specific feature of the current setup, linked to the shear layers separating from a relatively tall building in the considered canopy. <Pw> is the production rate of TKE in the wakes of roughness elements by the interaction of local turbulent stresses and time-averaged strains; in the lower UCL it is approximately constant, positive (WKE converts to TKE) of magnitude $\langle Pw \rangle^* \approx u_\tau^3/z_h$. <Pw> accounts for over 50% the total production rate of TKE in the UCL, and is therefore non-negligible. Our results suggest that in flows over realistic urban canopies the presence of street canyons aligned with the mean flow and of variable building geometry tends to increase <Pw> in the lower UCL, when compared to results of flow over strip canopies (Raupach et al., 1991). The additional form-induced production term $\langle P_m \rangle$ is non-zero only in the vicinity of the inflection layer z_γ, where it accounts for 16% the magnitude of $\langle P_s \rangle$.

DA transport terms are found to be non-negligible throughout the roughness sublayer. From Fig. 3 it is apparent how DA production terms ($\langle P_s \rangle + \langle P_w \rangle + \langle P_m \rangle$) overcome dissipation in the RSL down to z_h, and DA transport terms are responsible to remove TKE from this layer of high production, and transport it towards the wall to balance dissipation. In the upper RSL transport terms are thus negative, and contribute about 12% to the total sink rate of TKE. They change sign in the UCL, where they are of highest significance, contributing about 40% to the total rate of TKE. $\langle T_d \rangle$ appears as a modulation of $\langle T_t \rangle$, whereas $\langle T_p \rangle$ is significant at z_γ (where it is a sink of TKE) and in the very near wall regions, where it peaks at $\langle T_p \rangle^* = 0.8u_\tau^3/z_h$. Furthermore, we note the modest standard deviation in the computed $\langle T_t \rangle$ terms for both approaching wind directions. This is indicative of the poor sensitivity of the solution with respect to the specific SGS model and to the z_0 parameter, when the roughness is explicitly resolved through an IBM method.

DA dissipation $\langle \varepsilon \rangle$ peaks at z_γ, as displayed in Fig. 3. This is another peculiar feature of the current study, and is in contrast with results of flow over gravel beds

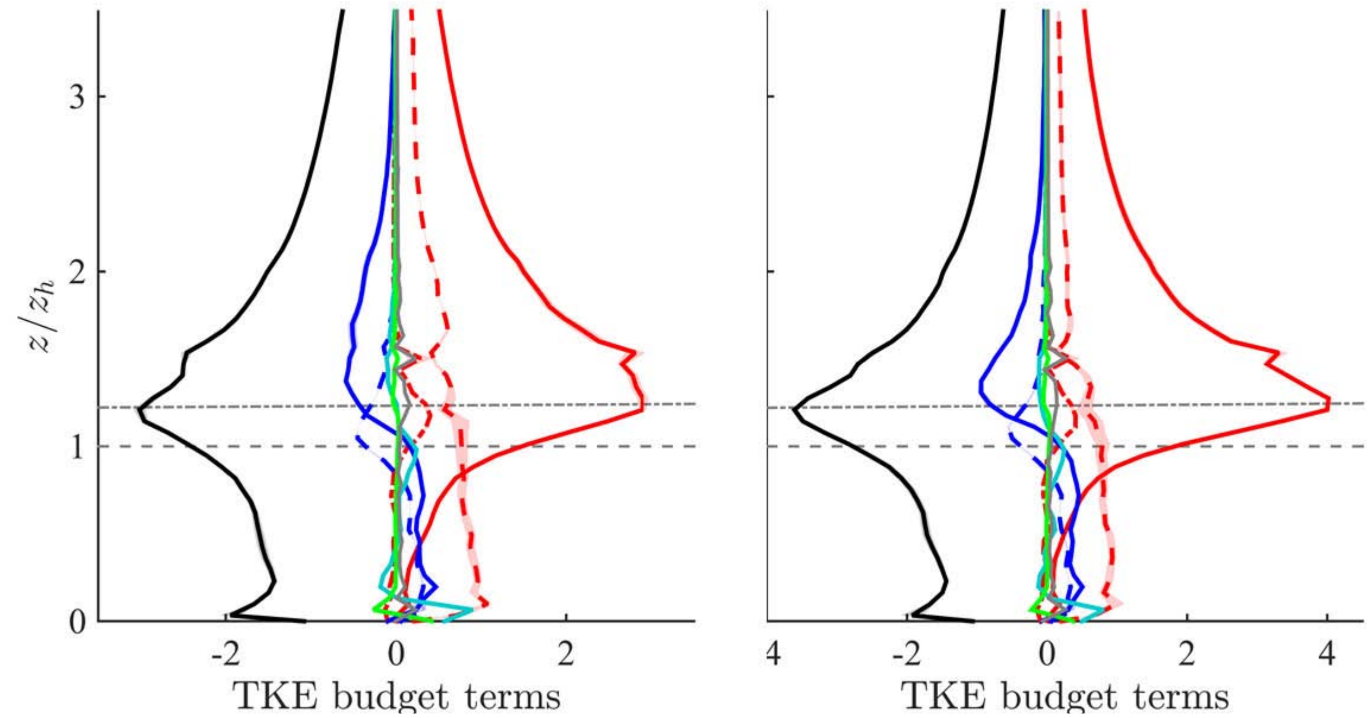


Figure 3. DA TKE budget terms for the across-canyon α = 156° wind direction. Notation: turbulent shear production <P_s>*, solid red line; wake production <P_w>*, dashed red line; form- induced production <P_m>*, dot-dashed red line; dissipation <ε>*, black; turbulent transport <T_t>*, solid blue line; dispersive transport <T_d>*, dashed blue line; pressure transport ⟨T_p⟩*, light blue; subgrid transport ⟨D⟩, green; residual, grey. Horizontal dashed and dot-dashed (grey) lines denote zh and zγ respectively. Only the lower 33% of the domain is shown.

(Mignot et al., 2009; Yuan and Piomelli, 2014), where the peak in dissipation was found to be shifted toward the wall, with respect to the peak in the shear production rate. Further, a strong rate of dissipation characterizes the near-wall regions. This peak is required in order to balance pressure transport of TKE from aloft, again confirming the important role of pressure transport in the vicinity of walls, in flows over directly resolved building interfaces. The small residual is likely due to interpolation of variables in the near interface regions (which are required to compute certain TKE budget terms), and leads to numerical truncation errors affecting the quality of the computed terms.

Conclusions

A characterization of TKE and of its budget terms has been performed via LES over a realistic urban canopy, representing a subset of the city of Basel. TKE profiles have been compared to direct tower measurements from a field campaign and found to be in good agreement, certifying the quality of the computations. DA TKE peaks above $z_γ$, in agreement with results from studies of flow over synthetic urban-like surfaces. TKE is significant in the UCL, when compared against results of flow over gravel beds and over regular / random arrays of cubes. Further, dispersive TKE is found to be non-negligible in the UCL, and of the same order of magnitude of its turbulent counterparts. Turbulent kinetic energy (TKE) in the UCL is primarily produced at $z_γ$ by shear, and is transported down into the cavities of the UCL (street canyons, backyards) by turbulent and dispersive transport terms, which share similar magnitudes. Transport terms are non-negligible throughout the RSL. They are of negative sign and contribute about 12% to the total variation rate of TKE in the RSL, whereas they are of highest significance in the UCL. Here, they are of positive sign and contribute about 40% to the local variation rate of TKE. Wake production is roughly constant up to $z_γ$ and of non-negligible magnitude, contributing up to 50% of the total TKE production rate in the UCL. Further, pressure transport is found to be a significant source of TKE in the near wall regions, in agreement with previous findings in flow over vegetation canopies and flow over gravel beds.

From our results it is also apparent that tower measurements cannot be used to quantify all terms in a horizontally-averaged view, because the non-measurable dispersive terms and pressure terms are important in a real canopy and should therefore be considered in future UCPs.

Acknowledgements

This work was supported by the Swiss National Science Foundation and by a grant from the Swiss National Supercomputing Centre (CSCS) under projects ID s404 and s599. AC and CM acknowledge the hospitality and support of EPFL during visits in 2012 and 2013, and MBP and AC are grateful for the support provided by an NSERC. The measurement of tower data was supported by the Swiss Ministry of Education and Science (Grant C00.0068).

References

Albertson JD, Parlange MB (1999) Surface length scales and shear stress: Implications for land-atmospheric interaction over complex terrain. *Water Resources Res* 35(7):2121–2132

Bou-Zeid E, Meneveau C, Parlange M (2005) A scale-dependent Lagrangian dynamic model for large eddy simulation of complex turbulent flows. *Physics of Fluids* 17(2):1–18

Britter RE, Hanna SR (2003) Flow and Dispersion in urban areas. *Annual Review of Fluid Mechanics* 35(1):469–496

Chester S, Meneveau C, Parlange MB (2007) Modeling turbulent flow over fractal trees with renormalized numerical simulation. *Journal of Computational Physics* 225(1):427–448

Christen A (2005) Atmospheric Turbulence and Surface Energy Exchange in Urban Environments. PhD thesis, University of Basel

Christen A, Rotach MW, Vogt R (2009) The budget of turbulent kinetic energy in the urban roughness sublayer. *Boundary-Layer Meteorology* 131(2):193–222

Coceal O, Thomas TG, Castro IP, Belcher SE (2006) Mean flow and turbulence statistics over groups of urban-like cubical obstacles. *Boundary-Layer Meteorology* 121:491–519

Kanda M, Inagaki A, Miyamoto T, Gryschka M, Raasch S (2013) A New Aero- dynamic Parametrization for Real Urban Surfaces. *Boundary-Layer Meteorology* 148(2):357–377

Mignot E, Barthelemy E, Hurther D (2009) Double-averaging analysis and local flow characterization of near-bed turbulence in gravel-bed channel flows. *Journal of Fluid Mechanics* 618:279

Raupach MR, Antonia Ra, Rajagopalan S (1991) Rough-Wall Turbulent Bound- ary Layers. *Applied Mechanics Reviews* 44(1):1

Rotach MW, Vogt R, Bernhofer C, Batchvarova E, Christen A, Clappier A, Feddersen B, Gryning SE, Martucci G, Mayer H, Mitev V, Oke TR, Parlow E, Richner H, Roth M, Roulet YA, Ruffieux D, Salmond Ja, Schatzmann M, Voogt Ja (2005) BUBBLE - An urban boundary layer meteorology project. *Theoretical and Applied Climatology* 81(3-4):231–261

Smagorinsky J (1963) General Circulation Experiments With the Primitive Equations. *Monthly Weather Review* 91:99–164

Xie ZT, Coceal O, Castro IP (2008) Large-Eddy simulation of flows over random urban-like obstacles. *Boundary-Layer Meteorology* 129(1):1–23

Yuan J, Piomelli U (2014) Roughness effects on the Reynolds stress budgets in near-wall turbulence. *Journal of Fluid Mechanics* 760:R1

Marco G. Giometto
mgiometto@gmail.com

School of Architecture, Civil and Environmental Engineering
École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

Andreas Christen
Geography/Atmospheric Science, UBC, Canada

Charles Meneveau
Mechanical Engineering, Johns Hopkins, USA

Jiannong Fang
Architecture and Engineering, EPFL, Switzerland

Marc B. Parlange
Civil Engineering, UBC, Canada

Transpiration of urban trees and its impact on daytime and nocturnal cooling in Gothenburg, Sweden

Figure 1. Photographs of the studied trees.

Introduction

Trees can mitigate heat stress in urban areas through shade and evapotranspiration (Mayer et al. 2009; Bowler et al. 2010; Shashua-Bar et al. 2011). However, in order to provide a cooling effect, urban trees need to remain healthy in spite of harsh growing conditions and stress factors absent or less severe in their natural environment (Roberts 1977). While transpiration of forest trees has been widely studied, little research has been conducted on the transpirative cooling effect of urban trees. Knowledge about the transpiration rates of urban trees and how these depend on environmental factors is essential for estimating the cooling effect provided by urban greenery as well as for appropriate urban planning and management to promote this ecosystem service.

Transpiration in darkness is often assumed to be negligible due to stomatal closure. However, several studies have reported non-negligible night-time stomatal conductance and transpiration of trees in forests and urban parks (Snyder et al. 2003; Fisher et al. 2007; Chen et al. 2011), with an average of 5-15% of the daytime values (Caird et al. 2007). While not directly measured, evening evapotranspiration has also been suggested by Lindén (2011) and Holmer et al. (2013) as a reason behind intensive nocturnal cooling of densely vegetated areas in the tropical city of Ouagadougou, Burkina Faso. The rapid cooling of vegetated areas in Ouagadougou around sunset, in the so-called Phase 1 of nocturnal cooling (Holmer et al. 2007), was accompanied by an increase of specific humidity not observed at non-vegetated sites, which cooled more slowly. In Phase 2, starting around 2-3 h after sunset, the cooling was less intensive, with small differences in cooling between vegetated and non-vegetated sites. Nocturnal cooling rates are of high importance in urban climate studies, as an enhanced cooling can lead to lower night-time air temperatures, providing relief from heat and decreasing heat-related mortality in urban areas (Rocklöv et al. 2011).

The aims of this study are to: i) quantify the magnitude and diurnal variations of transpiration of the most common urban tree species in Gothenburg, Sweden, ii) analyse the influence of meteorological conditions and surface permeability on the transpiration of urban trees and iii) find out whether transpiration of urban trees contributes to daytime or nocturnal cooling.

Methods

Study area – The study was conducted in Gothenburg (57°42'N, 11°58'E), the second largest city in Sweden. The city has a maritime temperate climate, with mean air temperature of 17.0°C in July and -1.1°C in February and mean annual precipitation of 758 mm (SMHI 2013). There are many green areas, but few street trees in the city. Deciduous trees, which are dominant, usually foliate in late April-early May and defoliate in October.

Seven common street tree species in Gothenburg were chosen for the study: *Tilia europaea* (Common lime), *Quercus robur* (English oak), *Betula pendula* (Silver birch), *Acer platanoides* (Norway maple), *Aesculus hippocastanum* (Horse chestnut), *Fagus sylvatica* (European beech) and *Prunus serrulata* (Japanese cherry). For each species, an urban site with 3 to 6 tree individuals of similar age and dimensions was chosen (Fig. 1). The study sites were characterized by different planting conditions, from small pits surrounded by impervious surfaces, to wide grass lawns. In the case of *T. europaea*, the most abundant tree species in Gothenburg, three study sites were chosen – one site located in a park (cemetery) as well as two sites along streets with different lawn width.

Transpiration measurements − Stomatal conductance (g_s, mmol m^{-2} s^{-1}) and transpiration rate (E_L, mmol m^{-2} s^{-1}) per unit one-sided leaf area were measured using a Li-Cor LI-6400XT Portable Photosynthesis System (LI-COR, Lincoln, USA) with a transparent leaf chamber, under ambient air temperature and humidity, and with a CO_2 mole fraction of 400 µmol mol^{-1}.

The measurements were conducted during daytime (around the time of solar noon, i.e. UTC + 1) and nighttime (1-4 h after sunset) on warm summer days of 2012-2013. At most sites, measurements were conducted on two days at each site, with one day cloud-free and one day with low to moderate cloudiness. Due to weather conditions and instrument unavailability, measurements of *Acer platanoides*, *F. sylvatica* and *T. europaea* park trees were only conducted on one day.

Both g_s and E_L were measured at low crown level, at the height of around 2 m, on four leaves per tree: two fully sunlit and two shaded during daytime. Since the selected trees were well exposed to sunlight, measurements at this height could be made on fully sunlit leaves. To analyse the diurnal variation of transpiration of street and park trees in more detail, measurements of *T. europaea* (at three different study sites) and *F. sylvatica* were conducted every hour from noon until a few hours after sunset.

Leaf area index (one-sided foliage area per unit ground area, LAI, m^2 m^{-2}) of the studied trees was measured using a LAI-2200 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln, USA) and recomputed in FV2200 v. 1.2 software, following guidelines for isolated canopy measurements provided in the instrument manual (LI-COR 2009). LAI values ranged from 2.5 for *T. europaea* street trees growing in narrow grass lawns along a heavy traffic road (Fig. 1b) to 7.8 for *F. sylvatica* park trees, Fig. 1h), with an average of 5.0. In order to scale up daytime E_L values, the ratio of sunlit (LAI_{sun}) to shaded (LAI_{shade}) leaves was then estimated assuming a random leaf angle distribution, common in broadleaf tree species (Chen et al. 1997). Transpiration (E_G, mmol m^{-2} s^{-1}) and energy loss (Q_E, W m^{-2}) per unit of vertically projected tree crown area were then calculated by scaling up E_L using the obtained LAI_{sun} and LAI_{shade} values. For a detailed description of the LAI measurement and computation, see Konarska et al. (2015).

Meteorological data − Air temperature (T_a) and relative humidity (RH) were recorded at each site during the transpiration measurements using a TinyTag Plus 2 logger (Gemini Data Loggers, Chichester, UK), with time resolution of 1 minute. The logger was placed in a radiation shield on one of the studied trees, on the northern side of its trunk, 2 m above the ground. From T_a and RH, vapour pressure deficit (VPD) was calculated. 30-minute average values of T_a were used to calculate warming/cooling rates during the daytime and nocturnal measurements. Despite small variations in the timing of daytime measurements, warming rates were calculated between 11 a.m. and 1 p.m. for consistency, as the daytime warming rate is strongly affected by incoming solar radiation. Moreover, diurnal courses of T_a and cooling rates were analysed to find out the timing of the two phases of nocturnal cooling – the intensive, site-specific cooling around sunset (Phase 1) and the less intensive, spatially homogeneous cooling later in the night (Phase 2). The hourly transpiration measurements (conducted in the period between 1 to 4 h after sunset) were then grouped into Phase 1 and Phase 2. For a detailed explanation of the two phases, see Holmer et al. (2007).

In addition, simultaneous T_a and RH measurements were conducted using another TinyTag Plus 2 logger at a reference urban site with no vegetation. The two loggers were inter-compared before and after measurements and showed a narrow range of T_a readings (0.1°C at ambient T_a of 20°C). The reference site was located less than 1 km east from the city centre, in a street canyon with a sky view factor (SVF) of 0.46. Since the nocturnal cooling is strongly affected by SVF, data from the reference site were only used for comparison with transpiration measurement conducted at sites characterised by a similar SVF (SVF > 0.30, i.e. sites b, d, e, f in Fig. 1).Meteorological data (incoming solar radiation and precipitation) were also collected from a weather station located at the rooftop level in the city centre, within 3 km from the measurement sites.

Results and discussion

The diurnal variation of transpiration − Measured midday E_L (1-3 mmol m^{-2} s^{-1}) and g_s (45-218 mmol m^{-2} s^{-1}) were in a similar range to those reported in other studies on urban trees (Cregg 1995; Rahman et al. 2011)(Fig. 2). *Q. robur*, described by Aasamaa et al. (2002) as a drought-tolerant species, had the highest g_s and E_L of all trees measured in this study. The water use of *T. europaea* was relatively low. Whitlow and Bassuk (1988) and Whitlow et al. (1992) attributed the low water use of this species to its high sensitivity to drought. Intra-species variations in E_L caused by different weather or growing conditions were also observed, particularly in sunlit leaves. In the cases of *Q. robur* and *B. pendula*, significantly higher E_L of sunlit leaves was observed on the warmer, drier and sunnier of two measurement days, while the E_L rates of shaded leaves were comparable despite varying weather conditions.

As a result of decreasing incoming solar radiation and VPD, E_L started to drop around 2-3 h before sunset at each site (not shown). However, transpiration remained active after sunset in all trees studied, indicating an in-

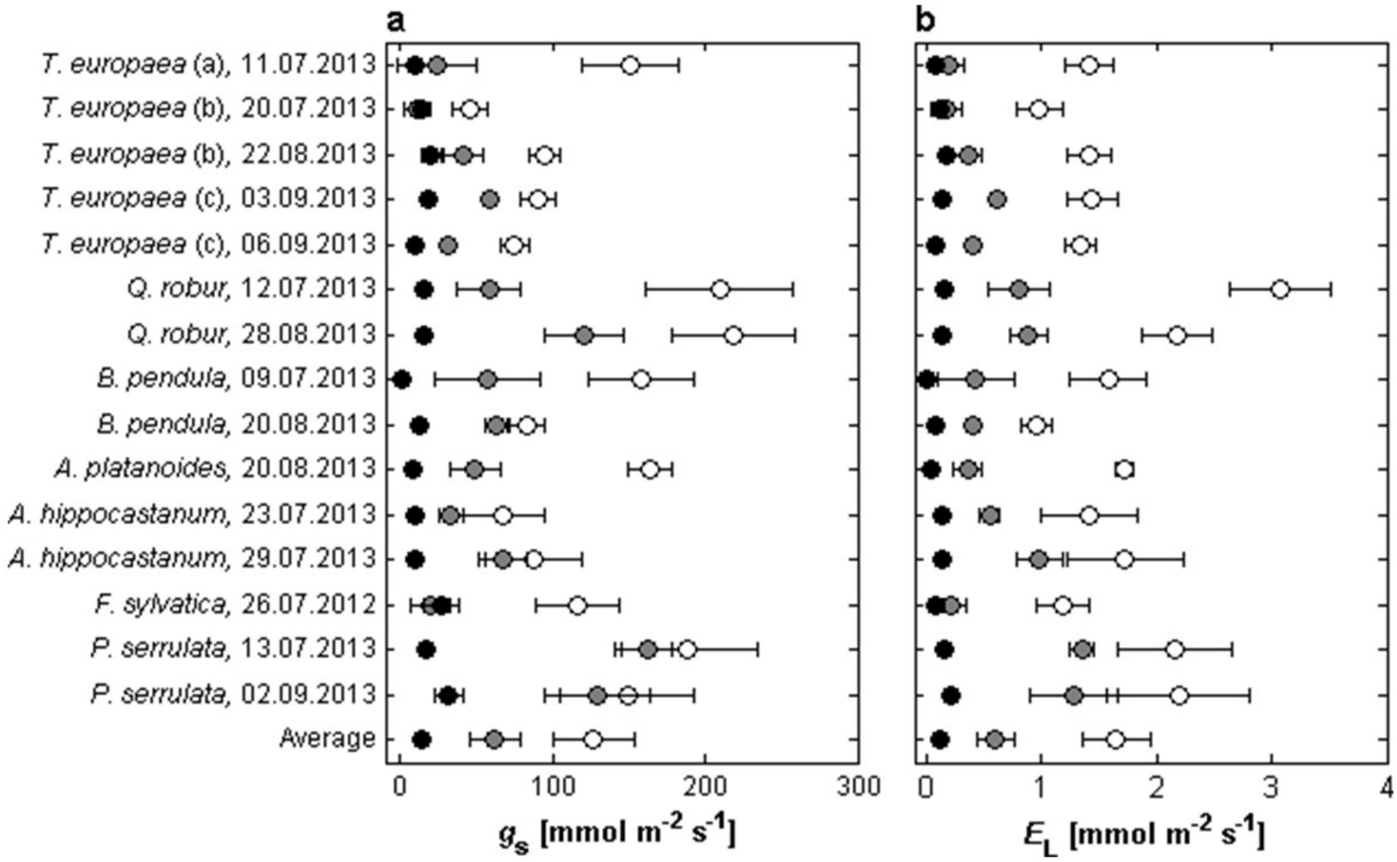


Figure 2. Average and standard deviation of midday and night-time: a) stomatal conductance (g_s, mmol m^{-2} s^{-1}) and b) transpiration rate (E_L, mmol m^{-2} s^{-1}). Midday sunlit, midday shaded and night-time values are represented by white, grey and black dots, respectively.

complete stomatal closure during night-time (Fig. 2). The night-time E_L values were stable from around sunset until the end of the measurements (1-4 h after sunset) and possibly longer. On average across species, night-time E_L reached 7% of midday E_L of sunlit leaves and 20% of those in shadow. These values are in good agreement with those reported in other studies, ranging from 5 to 19% (Snyder et al. 2003; Caird et al. 2007). In general, the highest night-time transpiration was observed in those trees which had the highest water loss during daytime, with daytime and night-time E_G being positively correlated ($R^2 = 0.35$, $p = 0.02$). A similar positive relationship was reported by Snyder et al. (2003) in a hot, dry environment of the western US.

Influence of water supply and growing conditions – Midday E_L and g_s of sunlit leaves were related to the sums of precipitation in periods from 5 to 30 days prior to measurements. The precipitation sum within 20 days prior to measurements was found to explain 38% of variance in g_s, indicating a strong stomatal response to soil water availability (Fig. 3a). In general, at the sites where measurements were conducted on two days, transpiration rates were in all cases lower after the 20-day period with lower precipitation sum, regardless of VPD, T_a or cloudiness. Relationships with precipitation sums in periods shorter or longer than 20 days were weaker ($R^2 < 0.16$) and statistically insignificant.

Among the seven studied tree species, *Q. robur* and *P. serrulata* had the highest values of E_L of sunlit leaves. At these two sites trees were planted on 8-18 m wide grass lawns (Fig. 1d, Fig. 1i). In contrast, the lowest E_L values were measured for *T. europaea* growing along a heavy-traffic road (Fig. 1b), and for *B. pendula* (Fig. 1f). Both of these sites have poor growing conditions, with the trees surrounded mostly by paved surfaces and planted within a short distance from a road. Trees with a higher proportion of permeable surfaces within the vertically projected tree area were found to have a higher g_s than those surrounded by impervious surfaces (Fig. 3b). Higher transpiration, water loss, net photosynthesis and/or biomass production in trees growing over grass in comparison to those surrounded by impervious surfaces were also observed in urban trees in different climate zones (Close et al. 1996; Celestian and Martin 2005; Ferrini and Baietto 2007).

In order to roughly estimate the amount of water available for the trees, the sum of precipitation in 20 days prior to measurements was multiplied by the proportion of permeable surfaces within the vertically projected tree crown area (Fig. 3c). Although this crude measure of tree water availability does not account for soil characteristics, rain interception or the extent of roots, it explained 68% of the variance in g_s across all midday data. It is thus a suitable tree water availability index for urban trees that can serve as a proxy for more difficult and expensive measurements of soil water content and availability.

Latent heat flux and the cooling effect – With the estimated mean midday energy loss due to tree transpiration of 206 W m^{-2}, on average 30% of incoming solar radiation was converted into the latent heat flux within the vertically projected tree crown (not shown). Midday to early afternoon evapotranspirative energy loss per unit of vertically projected crown area estimated for street trees in Manchester, UK by Rahman et al. (2011) was several times higher, amounting to over 1000 W m^{-2}. However, as noted by the authors, the energy loss of Manchester trees was likely overestimated, since the up-scaling from leaf to tree transpiration was based on the assumption that all leaves transpired at the same rate as the measured sunlit leaves. Our data showed that this is an invalid assumption since sunlit leaves transpired at rates three times as high as those of leaves in the shade.

Figure 4 shows the relationship between night-time (a) and midday (b) E_L and the corresponding cooling/warming rate, measured by a T_a logger at each site. In Phase 1 of nocturnal cooling, a higher E_L corresponded with a more intensive cooling ($R^2 = 0.51$, $p = 0.03$). On average, with an increase of E_L by 0.1 mmol m^{-2} s^{-1}, cooling rate intensity in Phase 1 increased by 0.25°C h^{-1} (Fig. 4a). Although the night-time energy loss caused by transpiration was significantly lower than during daytime (on average 24 W m^{-2}, not shown), it could still contribute to the evening cooling due to higher stability of the air and a shallow depth of the cooled air layer. While during the day the well mixed urban boundary layer can extend vertically up to over 1 km, at night-time its depth is limited to 100-300 m or less (Oke 1987; Eliasson and Holmer 1990). It should be noted that the relationship between cooling rates and E_L could be affected by varying meteorological conditions on different measurement days, with clear, warm weather enhancing both radiative cooling and tree transpiration. However, the contribution of transpiration to the evening cooling was also indicated by the less intensive cooling observed at a non-vegetated reference site with a similar SVF. While transpiration was also observed later in the night, in Phase 2, it was no longer correlated with the cooling rate, possibly due to the development of a capping inversion leading to a spatially uniform cooling (Holmer et al. 2013). No significant correlation was found between midday E_L and the warming rate of the air, as the strong vertical and horizontal mixing of the air suppresses the cooling effect of intensive daytime transpiration (Fig. 4b). This result is in line with a review by Bowler et al. (2010), where a more

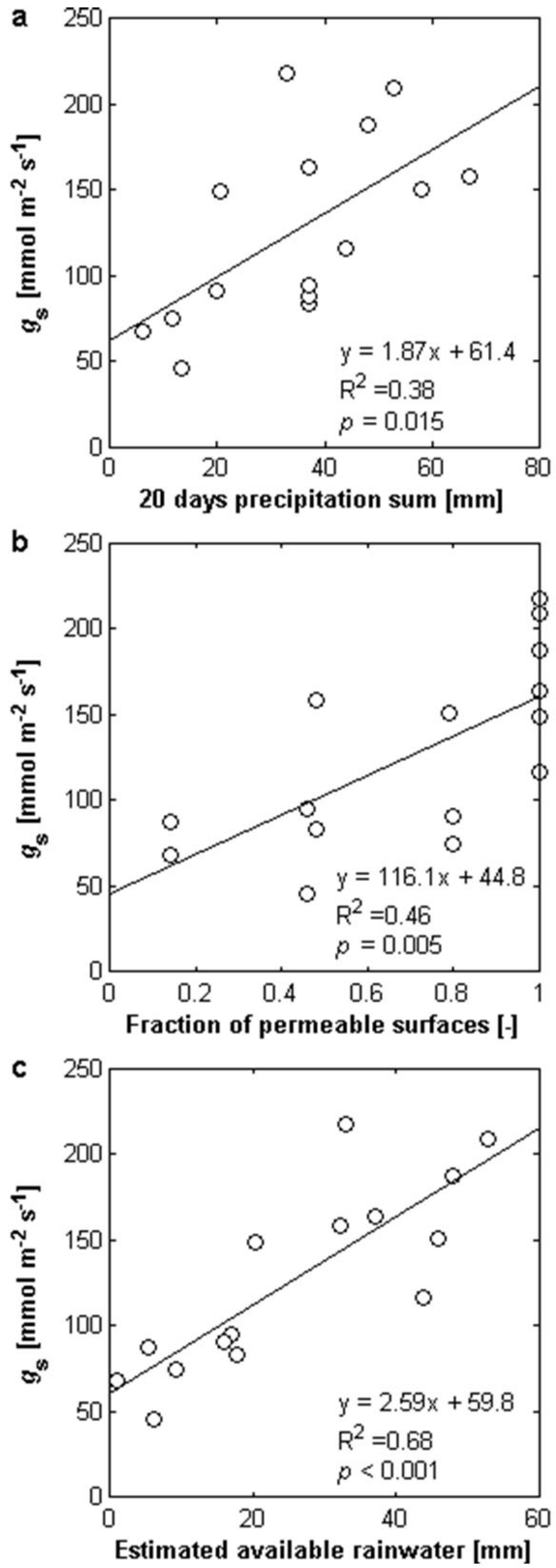


Figure 3. Midday stomatal conductance (g_s) of sunlit leaves vs: a) 20 days precipitation sum, b) fraction of permeable surfaces within the vertically projected tree area, c) their product used as an estimation of available rainwater. Each point represents a different measurement day.

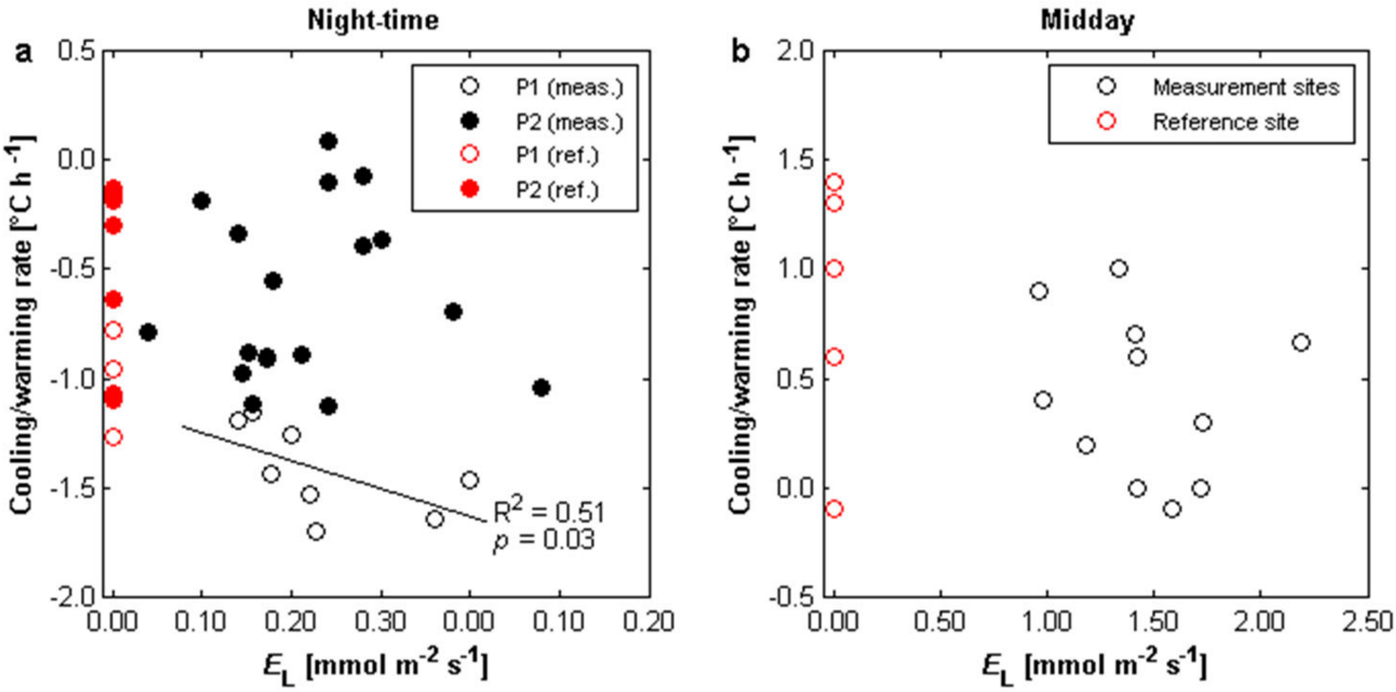


Figure 4. Night-time (a) and daytime (b) leaf transpiration rate (E_L, mmol m^{-2} s^{-1}) versus cooling/warming rate of the air (°C h^{-1}) at the transpiration measurement sites (black dots) and a non-vegetated reference site (red dots). Night-time data are divided into two phases of nocturnal cooling – Phase 1 (P1) lasting until 2-3 h after sunset, and Phase 2 (P2) lasting for the rest of the night. Each point represents a mean hourly value.

intensive mean night-time than daytime cooling effect of urban vegetation was reported. It should be noted, however, that despite a limited effect on daytime warming rates or T_a, street trees can significantly reduce the heat stress on summer days by providing shadow (Shashua-Bar et al. 2011, Konarska et al. 2014). The slightly more intensive midday warming rates at the reference site were presumably caused by a stronger sun exposure of the non-vegetated street canyon than the measurement sites shaded by a tree canopy.

Conclusions

Midday leaf transpiration measured on summer days on mature street and park trees in Gothenburg, Sweden, ranged from less than 1 to over 3 mmol m^{-2} s^{-1} for different species, with on average 30% of incoming solar radiation being converted into latent heat flux at midday. Midday stomatal conductance had a positive correlation with the fraction of permeable surfaces within the projected tree crown area. Multiplying this ratio by the precipitation sum in 20 days prior to measurements gave a simple, rough estimate of available rainwater, which was found to explain 68% of variance in stomatal conductance. The observed variations in transpiration rates identified a need for a further study focusing on inter-species variations in transpiration rates under different meteorological and growing conditions.

Night-time transpiration was observed in all studied species and amounted to 7% and 20% of midday transpiration rate of sunlit and shaded leaves, respectively, with an estimated latent heat flux of 24 W m^{-2}. A positive correlation of transpiration rate with the cooling rate of the air and a less intensive cooling at a non-vegetated reference site indicated a contribution of tree transpiration to cooling around and shortly after sunset. No transpirative cooling effect was observed later in the night or during daytime.

Acknowledgments

The project was funded by the Swedish Research Council Formas (259-2012-887 and 214-2010-1706), Swedish Transport Administration and Mistra Urban Futures. Special thanks are due to Malin Löfstrand and Elise Nässén for permission to conduct measurements in Trädgårdsföreningen and Stampen parks, respectively, as well as to Thomas Berg Hasper and Ignacio Ruíz Guzman for help with the measurements.

References

Aasamaa K., Sõber A., Hartung W., Niinemets Ü., 2002: Rate of stomatal opening, shoot hydraulic conductance and photosynthetic characteristics in relation to leaf abscisic acid concentration in six temperate deciduous trees. *Tree Physiology* 22:267-276.

Bowler D.E., Buyung-Ali L., Knight T.M., Pullin A.S., 2010: Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc Urban Plann* 97:147-155. doi:10.1016/j.landurbplan.2010.05.006

Caird M.A., Richards J.H., Donovan L.A., 2007: Night-time stomatal conductance and transpiration in C3 and C4 plants. *Plant Physiol* 143:4-10.

Celestian S.B., Martin C.A., 2005: Effects of parking lot location on size and physiology of four southwestern US landscape trees. *J Arboric* 31(4):191-197.

Chen, J.M., Blanken P.D., Black TA, Guilbeault M, Chen S., 1997: Radiation regime and canopy architecture in a boreal aspen forest. *Agricultural and Forest Meteorology* 86(1):107-125.

Chen L., Zhang Z., Li Z., Tang J., Caldwell P., Zhang W., 2011: Biophysical control of whole tree transpiration under an urban environment in Northern China. *J Hydrol* 402:388-400.

Cregg B.M., 1995: Plant moisture stress of green ash trees in contrasting urban sites. *J Arboric* 21:271-276.

Eliasson I., Holmer B., 1990: Urban heat island circulation in Göteborg, Sweden. *Theor Appl Climatol* 42:187-196.

Ferrini F., Baietto M., 2007: Effect of compost-amended backfill and paved surface on leaf parameters and physiology of Norway Maple (Acer platanoides L.). *Arboric Urban For* 33:386-391.

Fisher J.B., Baldocchi D.D., Misson L., Dawson T.E., Goldstein A.H., 2007: What the towers don>t see at night: nocturnal sap flow in trees and shrubs at two AmeriFlux sites in California. *Tree Physiology* 27:597-610.

Holmer B., Thorsson S., Eliasson I., 2007: Cooling rates, sky view factors and the development of intra-urban air temperature differences. *Geogr Ann Ser A-Phys Geogr* 89A:237-248.

Holmer B., Thorsson S., Lindén J., 2013: Evening evapotranspirative cooling in relation to vegetation and urban geometry in the city of Ouagadougou, Burkina Faso. *Int J Climatol* 33:3089-3105.

Konarska J., Lindberg F., Larsson A., Thorsson S., Holmer B., 2014: Transmissivity of solar radiation through crowns of single urban trees—application for outdoor thermal comfort modelling. *Theor Appl Climatol* 117:363-376.

Konarska J., Uddling J., Holmer B., Lutz M., Lindberg F. Pleijel H., Thorsson S., 2015:. Transpiration of urban trees and its cooling effect in a high latitude city. *Int J Biometeorol*, 1-14.

LI-COR, 2009: LAI-2200 Plant Canopy Analyzer Instruction Manual. ftp://ftp.licor.com/perm/env/LAI-2200/Manual/LAI-2200_Manual.pdf. Accessed 16 June 2014.

Lindén J., 2011: Nocturnal cool island in the Sahelian city of Ouagadougou, Burkina Faso. *Int J Climatol* 31:605-620.

Mayer H., Kuppe S., Holst J., Imbery F., Matzarakis A., 2009: Human thermal comfort below the canopy of street trees on a typical Central European summer day. *Ber Meteor Inst Univ Freiburg* 18:211-219.

Oke T.R., 1987: Boundary layer climates. 2nd edn. Methuen, London.

Rahman M., Smith J., Stringer P., Ennos A., 2011: Effect of rooting conditions on the growth and cooling ability of Pyrus calleryana. *Urban Forestry & Urban Greening* 10:185-192.

Roberts B.R., 1977: The response of urban trees to abiotic stress [Moisture, temperature, light, pesticides]. *J Arboric* 3(4): 75-78.

Rocklöv J., Ebi K., Forsberg B., 2011: Mortality related to temperature and persistent extreme temperatures: a study of cause-specific and age-stratified mortality. *Occup. Environ. Med*. 68: 531-536.

Shashua-Bar L., Pearlmutter D., Erell E., 2011: The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *Int J Climatol* 31:1498-1506. doi:10.1002/joc.2177

SMHI, The Swedish Meteorological and Hydrological Institute, 2013: http://www.smhi.se/klimatdata. Accessed 1 November 2013.

Snyder K., Richards J., Donovan L., 2003: Night-time conductance in C3 and C4 species: do plants lose water at night? *J Exp Bot* 54:861-865.

Whitlow T.H., Bassuk N.L., 1988: Ecophysiology of urban trees and their management: The North American experience. *Hortscience* 23:542-546.

Whitlow T.H., Bassuk N.L., Reichert D.L., 1992: A 3-year study of water relations of urban street trees. *J Appl Ecol*: 436-450.

Janina Konarska
janina.konarska@gvc.gu.se
Department of Earth Sciences
University of Gothenburg, Sweden

Johan Uddling	Björn Holmer
Martina Lutz	Fredrik Lindberg
Håkan Pleijel	Sofia Thorsson
Biological and Environmental Sciences	Earth Sciences

The urban cool island and atmospheric boundary layer dynamics

Introduction

The urban heat island (UHI) has been the focus in many studies, while a significant number of these studies document that cities often remain cooler than the countryside from the early morning until the early afternoon during fair weather and low wind speed conditions. This so-called urban cool island (UCI) may amount to 1–2 K (e.g. Kłysik and Fortuniak, 1999; Morris et al., 2001; Rotach et al., 2005; Chow and Roth, 2006). The UCI has been both observed and forecasted using atmospheric models (e.g. Miao et al. 2009; Salamanca et al., 2012); earlier studies qualitatively suggest that the UCI may originate from shadow effects in the urban canyon (Oke, 1982), the daytime energy storage in the urban fabric (Rotach et al., 2005), or the difference in land cover and the available soil moisture altering the surface energy balance (Georgescu et al., 2011). The current study explores an extended and more general physical explanation for the UCI that is rooted in atmospheric boundary-layer (ABL) dynamics.

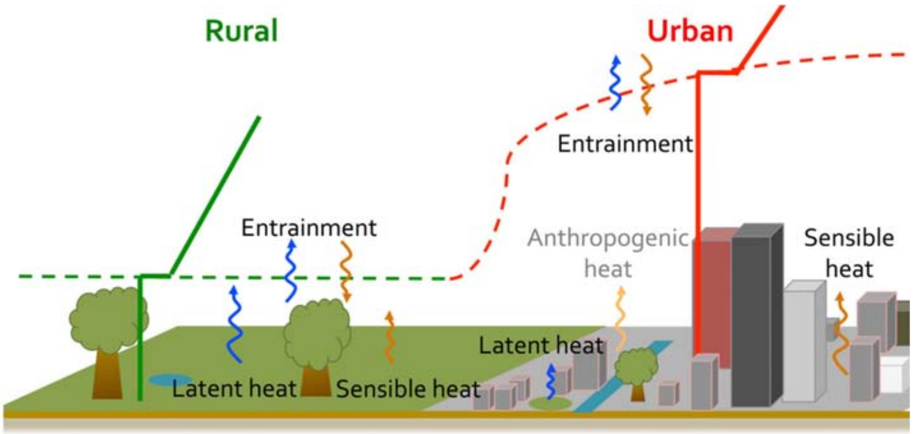


Figure 1. Schematic overview of the urban and rural ABL around sunrise. The potential temperature profiles display the schematic representation of the urban and rural ABL. The dashed line denotes the height of the rural (green) and urban (red) boundary layer.

The ABL is defined as the turbulent layer of the atmosphere closest to the Earth's surface. At night, the rural ABL cools and can be relatively shallow (~ 100 m, Bohnenstengel et al., 2014). On the other hand, the urban nocturnal ABL remains substantially deeper (~400 m, Oke, 1982; Bohnenstengel et al., 2014) because it remains supplied with heat stored in buildings during the day, the storage or ground heat flux. Here, we hypothesise that the difference between the thin rural ABL and the thick urban ABL causes a difference in heating rates between the urban and the rural environment in the early morning. As such, we expect that the countryside will warm up faster than the urban environment since the layer overlying the countryside is thinner and has a lower volume than the urban ABL.

The hypothesis will be evaluated using prognostic equations for the ABL height and potential temperature. This conceptual ABL model is initialized and evaluated with observations during the BUBBLE campaign in Basel, Switzerland (Rotach et al., 2005), where the UCI effect was observed during the intensive observation period (IOP) in the summer of 2002.

Methodology

Model formulation – Our hypothesis is based on the daytime ABL evolution and consequently a conceptual mixed-layer model (Tennekes, 1973) is appropriate to study the UCI. The mixed-layer model is a bulk model for the boundary layer and consists of a uniform virtual potential temperature and specific humidity below a sharp potential temperature and specific humidity inversion at the ABL top, and a linear increase (decrease) in the potential temperature (specific humidity) in the free atmosphere aloft (see Figure 1). This numerical bulk model is applied to the urban and the rural ABL and advection is neglected.

In order to represent the interactive processes between the land surface and the ABL, the surface fluxes for heat and moisture are calculated using a coupled land-surface parameterization valid for clear-sky conditions. The coupling of a land-surface parameterization gives realistic diurnal variations in the surface fluxes and allows for studying the sensitivity to urban surface properties.

Special care is taken to the storage or ground heat flux as this is one of the driving factors for the UHI and thus the higher urban ABL during the night. The storage heat flux is calculated following the objective hysteresis model by Grimmond and Oke (2002), and the sensible and latent heat flux are calculated using the Businger–Dyer relationships (Businger et al., 1971). In order to evaluate model results with observations at pedestrian level, we estimate the surface-layer air temperature from the ABL temperature.

Observations

The BUBBLE campaign is one of the rare datasets where boundary-layer observations are combined with surface observations and turbulent fluxes for both urban and rural sites and we are limited to this data from Basel, Switzerland (Rotach et al., 2005). In this study we selected the fair-weather days during the IOP in the BUBBLE campaign (one month during the summer of 2002), as these are conditions that are favourable for UCI formation (Morris et al., 2001). During this IOP there were 8 fair-weather days, of which one is described in detail here; the other cases can be found in Theeuwes et al., 2015.

Table 1 shows the initial conditions used in the mixed-layer equations for 26 June, 2002. The simulation is started at 5:00 local time (LT) with the observed ABL-UHI of 1°C and the observed urban and rural boundary-layer depths of 400 m and 100 m, respectively. The urban simulations are initialized and validated with data from site Basel-Spalenring (47.555 N; 7.576 E). The urban ABL height is estimated to be the aerosol mixed-layer height obtained from a Lidar situated at this site, where we assume an uncertainty of about 200 m (Hennemuth and Lammert, 2006). The rural simulations are initialized and validated with data from site Grenzach (47.537 N; 7.675 E). The rural ABL height is estimated from the vertical velocity of a doppler sodar system at this site. To this end we assumed the standard deviation of the vertical velocity was larger than 0.6 m s^{-1} in the ABL. Subsidence is derived from the European Centre for Medium-Range Weather Forecasts reanalysis vertical velocity above the ABL, averaged over the entire day.

Table 1. List of the default input variables into the mixed-layer equations as observed during 26 June, 2002 in Basel, Switzerland.

Variable	Rural	Urban
Initial mixed-layer potential temperature (K)	287	288
Initial mixed-layer temperature inversion (K)	5	4
Potential temperature lapse rate (K m^{-1})	0.007	0.007
Initial mixed-layer humidity (g kg^{-1})	8.7	9.1
Initial mixed-layer humidity inversion (g kg^{-1})	−0.1	−0.1
Humidity lapse rate (g kg^{-1} m^{-1})	−0.001	−0.001
Initial boundary-layer height (m)	100	400
Subsidence velocity (m s^{-1})	−0.00324	−0.00324

UCI formation

The model is initialized at sunrise with an urban ABL that is deeper (400 m) than the ABL over the rural area (100 m) following the observations (Figure 1). Note that these initial ABL heights are almost the same as found for London (Bohnenstengel et al., 2014). Figure 2 shows the modelled diurnal evolution of the convective ABL height, the air temperature and the UHI.

In the first 3.5 h after sunrise we find a heating phase with increasing temperatures over both the urban and rural area. During this phase the ABL is only heated by the input of the surface heat flux, while the ABL growth is marginal (Figure 2b). Although the urban surface heat flux is larger (~110 W m^{-2}) than the rural surface flux (~50 W m^{-2}), the urban heating rate is lower than the rural heating rate (maximum of 1.49 K h^{-1} versus 2.71 K h^{-1}) because the volume of air in the urban ABL that needs to be heated is much larger than the volume of air in the rural ABL. This finding corresponds to the earlier observations of a smaller heating rate in the urban environment compared to the rural environment (Oke, 1982; Johnson, 1985).

The larger heating rate in the rural environment causes the rural temperature to become higher than the urban temperature in the morning some two hours after sunrise. This causes the initial UHI (of 1 K) to shift to an UCI effect, with a maximum value of ~2 K (Figure 2c) approximately 4 h after sunrise.

In the second growing and heating phase, both the urban and rural ABL start to grow and warm from around 8:30 h due to the entrainment (mixing in of warm air from free tropospheric air) into the ABL. In this phase, the urban temperature increases more rapidly than the rural temperature due to the higher surface sensible heat flux

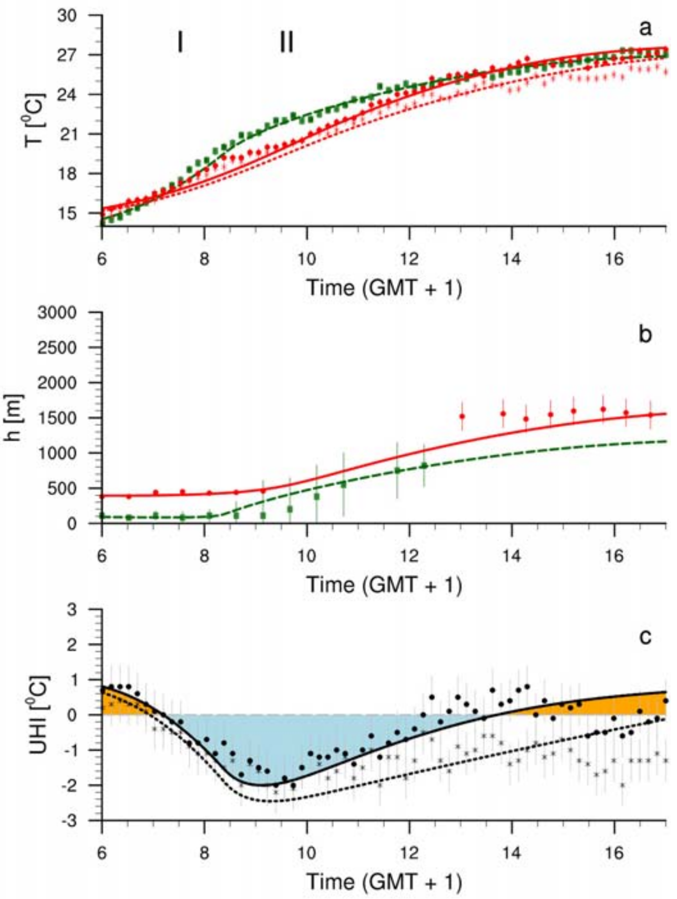


Figure 2. Diurnal evolution of the modelled (lines) and observed (markers) air temperature (a), boundary-layer height (b) and the urban heat island (c) in the urban (red) environment at 33 m (dotted lines and stars), at 3 m (solid lines and dots) and rural (green dashed lines and squares) environment. The measurements are for 26 June, 2002 at the urban measurement site Basel-Spalenring and the rural site Grenzach (Rotach et al., 2005). 'I' indicates the heating phase and 'II' the growing and heating phase.

of the city (maximum of ~330 Wm^{-2} versus ~180 Wm^{-2}). Ultimately, the urban temperature exceeds the rural temperature around 13:30 LT. This effect is also confirmed by the BUBBLE observations, which emphasizes the robustness of the proposed UCI mechanism.

Alternative explanations for the UCI such as shading, uptake of energy and the limited availability of soil moisture in the rural surroundings all stem from an alteration in the energy balance. This would, however, likely require the sensible heat flux of the rural environment to be higher than that of the urban environment. This is not shown to be the case here.

Conclusions

Cities are generally known for the evening and nocturnal UHI effects. Surprisingly, cities have been reported to be cooler in the morning and early afternoon. Our experiments provide a general explanation for this UCI. The nocturnal heat release from the urban surface leads to a deeper ABL over the city than over the countryside at sunrise. This difference in ABL depth induces a higher early morning heating rate over the countryside than over the city. Consequently, the initial UHI at the end of the night progresses into an UCI. This UCI peaks about 4 h after sunrise and can last into the early afternoon. For a case with an initial boundary-layer UHI of 1 K and urban and rural ABL heights of 400 and 100 m, the UCI reaches up to 2 K.

This research paves the way for new studies and could be extended to different cities. However, a limitation is the current lack of simultaneous measurements of the atmospheric boundary layer over urban and rural surfaces. In addition, the results of this study highlight the importance of including ABL dynamics in urban climate studies. Mesoscale atmospheric models can be used to elaborate this further. Different research perspectives also include the UCI implications for urban planning, health and air quality. The strong link between the UCI magnitude and the urban morphology indicates that the UCI can be employed as an efficient tool in urban planning and health.

Acknowledgments

This research was supported by NWO project CESAR as part of the program 'Sustainable accessibility to the Randstad' (grant 434_09_012). GJ Steeneveld and RJ Ronda acknowledge funding from NWO—EScience project 'Summer in the City' (grant 027.012.103). In addition, we would like to acknowledge funding from the WIMEK research fellowship for MW Rotach. Finally, we thank Jordi Vilà and Folmer Krikken for fruitful discussions.

References

Bohnenstengel S I et al 2014 Meteorology, air quality, and health in London: the ClearfLo project *Bull. Am. Meteorol. Soc.* 96 779–804.

Businger J A, Wyngaard J C, Izumi Y and Bradley E F 1971 Flux-profile relationships in the atmospheric surface layer *J. Atmosp. Sci.* 28 181–9.

Chow W T and Roth M 2006 Temporal dynamics of the urban heat island of Singapore *Int. J. Climatol.* 26 2243–60.

Georgescu M, Moustaoui M, Mahalov A and Dudhia J 2011 An alternative explanation of the semiarid urban area oasis effect *J. Geophys. Res.: Atmos.* 116 D24.

Grimmond C and Oke T R 2002 Turbulent heat fluxes in urban areas: observations and a local-scale urban meteorological parameterization scheme (LUMPS) *J. Appl. Meteorol.* 41 792–810.

Hennemuth B and Lammert A 2006 Determination of the atmospheric boundary layer height from radiosonde and lidar backscatter *Bound.-Layer Meteorol.* 120 181–200.

Johnson D 1985 Urban modification of diurnal temperature cycles in Birmingham, UK *J. Climatol.* 5 221–5.

Kłysik K and Fortuniak K 1999 Temporal and spatial characteristics of the urban heat island of Lódź, Poland *Atmos. Environ.* 33 3885–3895.

Miao S et al 2009 An observational and modeling study of characteristics of urban heat island and boundary layer structures in Beijing *J. Appl. Meteorol. Climatol.* 48 484–501.

Morris C J C, Simmonds I and Plummer N 2001 Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city *J. Appl. Meteorol.* 40 169–82.

Oke T R 1982 The energetic basis of the urban heat island *Q. J. R. Meteorol. Soc.* 108 1–24.

Rotach M W et al 2005 BUBBLE—an urban boundary layer meteorology project *Theor. Appl. Climatol.* 81 231–61.

Salamanca F, Martilli A and Yagüe C 2012 A numerical study of the urban heat island over Madrid during the DESIREX (2008) campaign with WRF and an evaluation of simple mitigation strategies *Int. J. Climatol.* 32 2372–86.

Tennekes H 1973 A model for the dynamics of the inversion above a convective boundary layer *J. Atmos. Sci.* 30 558–67.

Theeuwes NE, Steeneveld GJ, Ronda RJ, Rotach MW, Holtslag AAM. 2015. Cool city mornings by urban heat. *Environmental Research Letters* 10(11): 114 022.

Natalie Theeuwes
Natalie.Theeuwes@wur.nl
Meteorology & Air Quality
Wageningen University, The Netherlands

Gert-Jan Steeneveld, Reinder Ronda, Mathias Rotach,* Bert Holtslag

*Institute of Atmospheric and Cryospheric Sciences, University of Innsbruck, Austria

This report is part of the recently published article: Theeuwes NE, Steeneveld GJ, Ronda RJ, Rotach MW, Holtslag AAM. (2015) Cool city mornings by urban heat. *Environmental Research Letters* 10(11): 114 022.

Advanced Study Institute in Hong Kong addresses a changing urban climate and its impact on the thermal environment

Over 100 academics and scientists from all over the world gathered at the Chinese University of Hong Kong from 7th to 11th December for the **Croucher Advanced Study Institute (ASI) 2015**. This year's topic was "Changing Urban Climate and the Impact on the Urban Thermal Environment and Urban Living," and the lectures and discussions led by renowned academics and top Hong Kong government officials covered a wide range of topics along the two themes of urban climate and urban comfort.

It is the second time the team led by Yao Ling Sun Professor of Architecture Prof. **Edward Ng**, Associate Director of the Institute of Future Cities, and School of Architecture Assistant Professor Prof. **Chao Ren** host the Croucher Advanced Study Institute on the subject of urban climate, after a highly successful event in 2011 (which was reported in Issue No. 42 of *Urban Climate News*). The five-day programme addressed climate change as a major global challenge and highlighted the importance of incorporating climate information into urban planning and building design practice. It saw scientists, academics and architects exchange latest research findings on the topics of urban climate and comfort, from both the perspectives of science and practice.

Urban Climate

Speakers along the theme of Urban Climate centred their talks on the effect of urbanisation on climate, with many noting the fast urbanisation pace in recent years. Methodological, theoretical and practical aspects of the issue were covered, in hope of finding more effective ways to deal with future environmental risks.

Prof. **Alex Mahalov**'s opening lecture titled "High Resolution Earth System Models at Decadal and Regional Scales: Seeking Sustainable Solutions for Rapidly Expanding Urban Areas" was divided into two parts, one on designing mitigation strategies to manage extreme heat events in rapidly urbanising regions, and the other on multi-scale modelling of urban atmosphere in a changing climate. He pointed out that a holistic approach is needed in the design of strategies to manage extreme heat events and air quality challenges, and drew on case studies to introduce the impact of urbanisation on air quality.

Prof. **James Voogt**'s talk on "Urban Temperatures and Urban Heat Islands" introduced a hierarchy of scales to describe the urban surface and atmosphere, and Local Climate Zones as a relevant scheme to link urban science properties to thermal conditions. He discussed the

"Taking into account the fast pace of urbanisation, increasing densities in cities and rising energy consumption, climate change in an urban context is a major global challenge. It is important to incorporate climate information into urban planning and building design practice to adapt to and mitigate climate change, and to reduce its impact on city dwellers' health and comfort. "

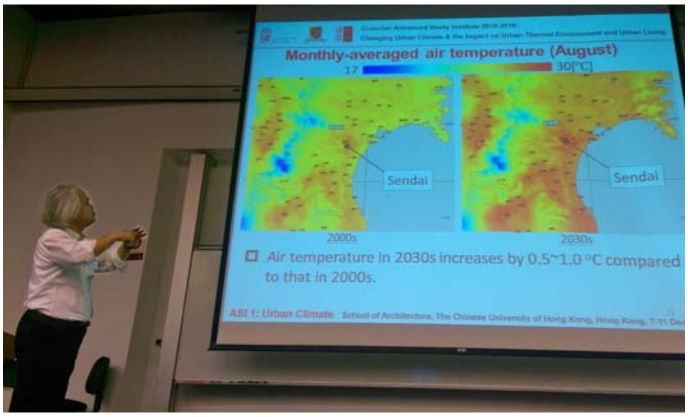
formation of urban thermal conditions and pointed out that measurements of temperatures should consider the relevant source area to match the observation to the relevant surface. He introduced the Lowry conceptual model as a useful tool to think about the measurement and interpretation of urban heat islands, and said urban actions to address heat islands should recognise the different types and processes of the condition. He concluded by saying future cities are likely to be hotter but urban heat island effects may not necessarily be larger, depending on how rural cooling rates are affected.

Prof. **Darren Robinson** spoke on "Urban Climate and the Broader Challenge of Urban Sustainability," touching on the complex systems and metabolism of cities. He emphasised the need for integrated urban modelling architecture in transition planning and noted that a flexible architecture could be applied to multiple spatial scales and time horizons. In the discussion section, topics including the definition of spatial and functional boundaries, modelling of phenomena influencing city sustainability, the design of a scalable platform and the definition and handling of uncertainties were discussed, with substantial input from the floor.

Dr. **Fei Chen** introduced the Weather Research and Forecasting (WRF) Model in his talk "Modelling Urban Environmental Risks under Future Climate Change". He spoke on its capabilities to deal with environmental risks associated with climate change by bridging the gap between the traditional mesoscale and fine-scale urban transport and dispersion modelling. Dr Chen noted the need to improve specification of urban parameters and to evaluate model performance. He then discussed the applications of WRF in an urban context, and pointed to the need for an integrated Atmosphere-Land-Urban-Aerosol modelling approach in predicting and assessing urban environmental problems.

In Prof. **Janet Barlow**'s presentation of "The Breathing City – Ventilation Processes from Building to City Scale", she focused on human and building ventilation, urban microclimates, street to neighbourhood scale pollution dispersion, urban boundary layer ventilation, and thermally driven flows, such as river, slope and sea breeze. She pointed out that ventilation of cities occurs at a range of scales, and some flow patterns can be influenced by good urban design, while some natural processed could be "exploited". She emphasized the non-linear and hard-to-measure natures of flow, and at the end posed the question to the audience of what "urban archetypes" are needed for more sustainable cities.

Prof. **Ryozo Ooka** presented on "The Effect of Climate Change on Urban Climate and Built Environment", giving special attention to air pollution and local heavy rain. He pointed out that the effect of climate change on urban environment should be considered as the summation of the effects on both global and urban scales. He called for a coupled simulation of global and urban climate models, noting the need to consider the effect of local and global climate on air pollution. He added that although it is very difficult to predict local heavy rain at present, analysis of its mechanism is possible.



Urban Comfort

Climate Change in an urban context could have drastic effect on urban dwellers' comfort. Speakers explored experimental designs, modelling and concerns in the design of urban environment for better human comfort.

Prof. **Rohinton Emmanuel**'s talk titled "Outdoor Thermal Comfort: Instruments, Methods, Standards and Value Ranges for the Tropics" reviewed approaches worldwide, introduced aspects of standardisations, drew on comparisons across the globe, and suggested the ways forward. He focused on experimental design, instruments, questionnaires and indices, and compared outdoor comfort thresholds in Rio de Janeiro, Jakarta, Singapore, Taiwan, the Mediterranean, and Glasgow. He called for guidance on experimental design, and efforts in standardising micrometeorological instruments and measurement methods. He also noted the need of standardising questionnaires regarding subjective thermal perception and personal information, suitable thermal comfort indices to assess thermal comfort and standardisation of reporting of outdoor thermal comfort studies.

Prof. **Richard de Dear** gave a lecture on "Urban Thermal Comfort Fundamentals", and noted that thermal comfort is part of the thermoregulatory loop. He noted that most of our knowledge and tools for understanding thermal comfort in outdoor and semi-outdoor settings have been borrowed from indoor environments, and that the steady-state heat balance notion in outdoor research may not always be appropriate. In the second part of his talk, he spoke on the "Counterpoint and Alliesthesia" in urban thermal comfort, and pointed out that positive allisethesia is based on contrasting combinations of skin and core temperature trends. A given thermal stimulus can be subjectively experienced as pleasant or unpleasant, as underpinned by the temporal dynamics and spatial variations in outdoor microclimates, he said.

Prof. **Akashi Mochida** spoke on "Evaluation of the Effects of Greening and Highly Reflective Materials from Three Perspectives—Mitigation of Global Warming, Mitigation of Urban Heat Islands and Adaptation to Urban Warming". He outlined the assessment systems, gave examples of total assessments and evaluated the effects of windows with heat ray retro-reflective film on the outdoor thermal environment using a radiant analysis method which considers directional reflection. In the second part of the lecture, Prof. Mochida gave a presentation on "Evaluation of the Health Risk in Urban Pedestrian Space based on the Total Analysis of Mesoscale and Microscale Climate". He introduced methods to evaluate heatstroke risks in urban pedestrian space in extremely hot summer conditions, and predict future risks by the dynamical downscaling from GCM to RCM.

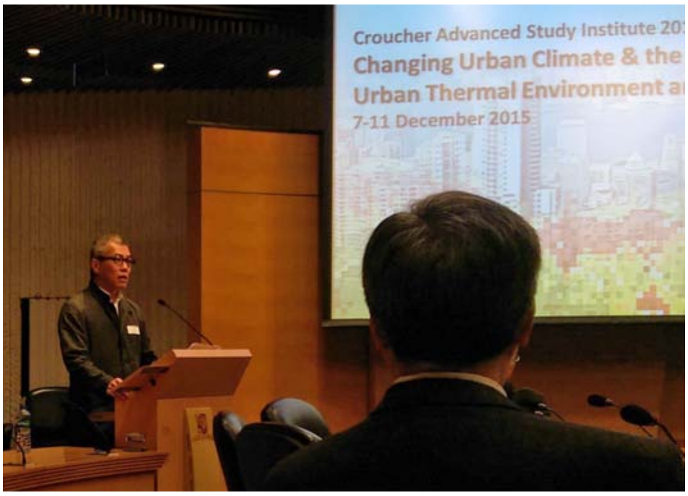
Prof. **David Pearlmutter** presented on "Designing Responsively: Pedestrian Thermal Stress in Hotter and Drier Cities". He pointed out that a warming climate may increase aridity and lead to expansion of dry climate zones, and even currently heavily urbanised regions such as Europe and East Asia could be affected. He called for more responsive design using urban geometry, trees, and materials. Drawing results from experimental studies, he suggested that the effective use of urban vegetation for reducing thermal stress in hot-arid cities requires a holistic planning approach, considering the geometry of the built urban fabric, in combination of with shade trees and vegetative ground cover, and the integration of drought-resistant plant species. At the end, he posed a question to the audience on the sustainability of different approaches to urban park design.

ASI 2015 was closed by Professor **Chris Webster**'s lecture on the "Healthy City" and a discussion afterwards.

Prof Webster explored the links between urban planning, architecture, private and public health, and introduced related works at the University of Hong Kong. He drew on the fact that agglomeration in cities first happened because of the potential to increase wealth, and thus health, but over-densification could lead to adverse health effects. He looked forward to future collaboration with the Chinese University of Hong Kong and between departments on the topic.

Conclusion

Taking into account the fast pace of urbanisation, increasing densities in cities and rising energy consumption, climate change in an urban context is a major global challenge. It is important to incorporate climate information into urban planning and building design practice to adapt to and mitigate climate change, and to reduce its impact on city dwellers' health and comfort. Topics such as climate change, urban heat islands, fast urbanisation, smart city and ageing could foreseeably become more important in both the fields of academia and public policies. Challenges including data derivation, compact cities, urban morphology and archetypes, thermal assimilation and health, risk and impact assessment, and benefits and co-benefits deserve more attention and are to be tackled only with wide collaborations.



To address some of the issues mentioned above, initiatives such as WUDAPT and Protocols for Outdoor Thermal Comfort Assessment and Reporting (OuTCAR Protocols) have been raised. It is worth noting that two important initiatives – WUDAPT Urban Database for Chinese Cities and Urban Thermal Comfort Protocol and Framework – have originated from the two ASI symposiums. The former would help researchers more easily to conduct their research on urban climate of Chinese cities, while the latter one would help people to have a standardised way of carrying out outdoor thermal comfort studies.

Acknowledgement

ASI was fully sponsored by the Croucher Foundation, and supported by different parties including professional institutions, government departments, and also different departments and research units in local universities, such as the International Association for Urban Climate, Hong Kong Green Building Council, Environment Bureau, Hong Kong Observatory, and Planning Department of HKSAR Government, Ove Arup & Partners Hong Kong Ltd. and the Institute of Environment, Energy and Sustainability (IEES).

Second WUDAPT Workshop focuses on Mapping Urban Landscapes

The second workshop on World Urban Database and Access Portal Tools (WUDAPT) was held at the School of Architecture, Chinese University of Hong Kong in December, following the Croucher Advanced Study Institute (ASI) on the preceding week.

The two-day workshop on 12th and 13th December focused on "Mapping Urban Landscapes and the Climate Effects", and followed the important initiative "WUDAPT Urban Database for Chinese Cities" being raised in the last ASI in 2011. The workshop is co-organised by the School of Architecture at the Chinese University of Hong Kong, the Planning and Environmental Policy unit at the School of Geography at University College Dublin, the University of North Carolina, and the International Institute for Applied Systems Analysis.

The workshop focused on the physical layout of cities (especially those in China) using the data gathered to this point in WUDAPT. Researchers examined how this information can be used to compare cities and guide their future development using climate models. In addition, in the workshop participants discussed the acquisition of more detailed urban data and possible ways to develop Level 1 data and link to urban climate space units and architectural types.

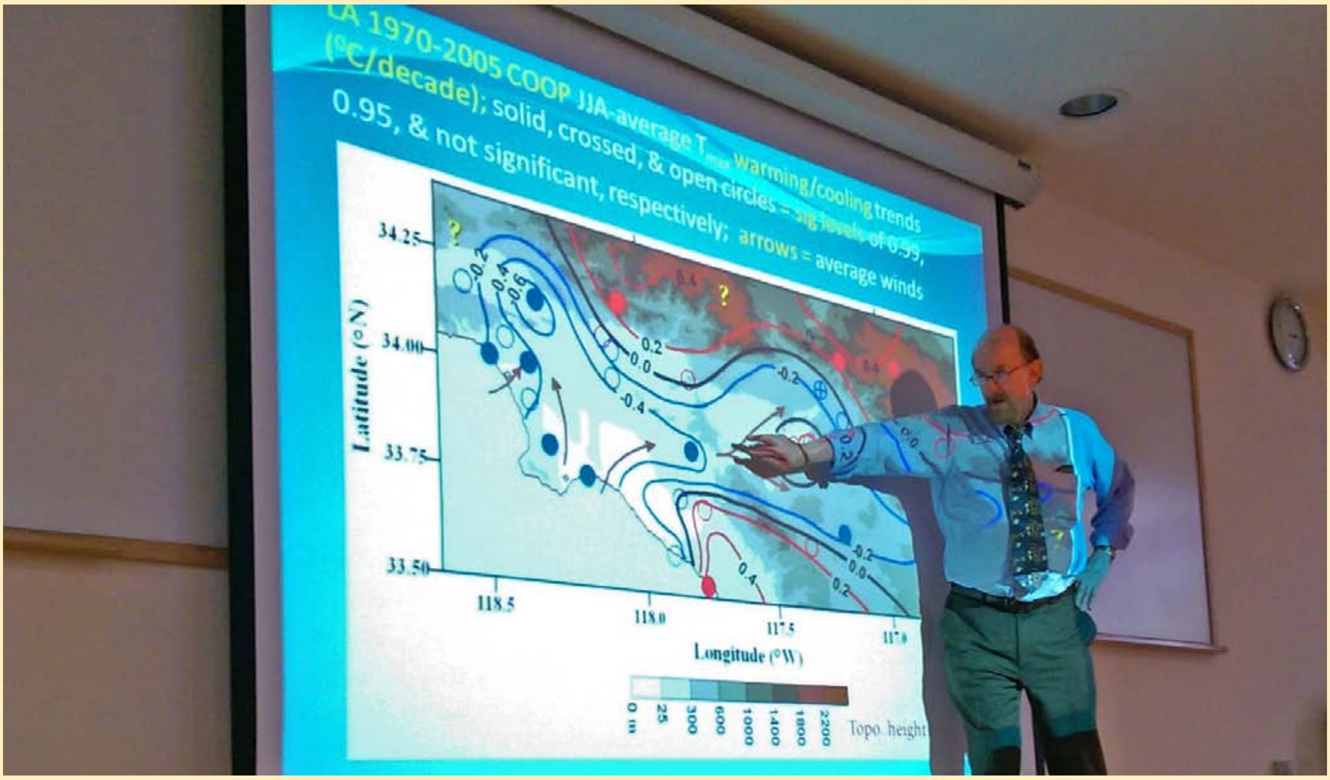
Speakers included Dr. **Gerald Mills**, Dr. **Jason Ching** and Dr **Iain Stewart**, who, together with **Paul Alexander** and **Michael Foley**, held a series of workshops on Level 0 WUDAPT data, Local Climate Zones (LCZs), comparing city maps, climate models, data collection,

and the use of the LUMPS model. The structure of the workshop reflects the design of a WUDAPT project. The first day was dedicated to the understanding of urban landscape characteristics using the LCZ system and a demonstration of how LCZ maps are generated, while the second day focused on the use of the data to make informed decisions about the form and functions of cities using simple models.

The ultimate goal of the WUDAPT project is to develop a detailed urban database with open access for all major cities in the world, contributing to a wide range of activities, such as planning for climate resilience, energy modelling and greenhouse gas assessment. As pointed out at various times during the workshop, there is plenty of room for further development and refinement. It is hoped that the workshop helped researchers develop better understanding of the project and induced further contribution. (Further information can be found at: http://www.wudapt.org/).

ASI 2015 included a tour of the Hong Kong Observatory, where the city's distinctive subtropical climate has been tracked for more than 130 years.

On November 14th, an 80-year birthday celebration was held at Kyoto University for **Prof. Yasuto Nakamura**. Prof. Nakamura was an organizer of the very first ICUC, which was held in Kyoto in 1989, and now he is a Professor Emeritus of Kyoto University. He has made many contributions to urban climatology and biometeorology, and the urban climate community wishes him a long and healthy life.



Prof. Bob Bornstein traced four decades of research on the urban atmosphere at a workshop in Tel Aviv November 18th-19th entitled "Urban Meteorology: Monitoring, Modeling and Environmental Aspects." The event was sponsored by the Israel Meteorological Society, and combined both theoretical and applied aspects of urban climate in a stimulating cross-disciplinary program.

Recent Urban Climate Publications

In this edition a list is presented of publications that have generally come out between **September and November 2015**. As usual, papers published since this date are welcome for inclusion in the next newsletter and IAUC online database. Please send your references to the email address below with a header "IAUC publications" and the following format: Author, Title, Journal, Year, Volume, Issue, Pages, Dates, Keywords, URL, and Abstract. In order to make the lives of the Bibliography Committee members easier, please send the references **in a .bib format**.

Since the ICUC9 in Toulouse, the bibliography committee has undergone some changes. I would now also like to introduce Lech Gawuc (Warsaw University of Technology, Poland) as a new member. Welcome to the committee! Please note that we are still supporting (young) researchers to join and contribute to the Committee. If you are interested to join or would like to receive more information, please let me know via the email address below.

Regards,

Matthias Demuzere

Department of Earth and Environmental Sciences, KU Leuven, Belgium

matthias.demuzere@ees.kuleuven.be

Aboshosha H, Elshaer A, Bitsuamlak GT, Damatty AE (2015) Consistent inflow turbulence generator for LES evaluation of wind-induced responses for tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 142:198-216.

Acero JA, Herranz-Pascual K (2015) A comparison of thermal comfort conditions in four urban spaces by means of measurements and modelling techniques. *Building and Environment* 93, Part 2:245-257.

Acosta I, Munoz C, Esquivias P, Moreno D, Navarro J (2015) Analysis of the accuracy of the sky component calculation in daylighting simulation programs. *Solar Energy* 119:54-67.

Allegrini J, Dorer V, Carmeliet J (2015) Influence of morphologies on the microclimate in urban neighbourhoods. *Journal of Wind Engineering and Industrial Aerodynamics* 144:108-117.

Alrawashdeh H, Stathopoulos T (2015) Wind pressures on large roofs of low buildings and wind codes and standards. *Journal of Wind Engineering and Industrial Aerodynamics* 147:212-225.

Amanollahi J, Tzanis C, Ramli MF, Abdullah AM (2016) Urban heat evolution in a tropical area utilizing Landsat imagery. *Atmospheric Research* 167:175-182.

Angelidis D, Assimakopoulos VD, Bergeles G (2015) A Cartesian grid refinement method for simulating thermally stratified urban environments. *Journal of Wind Engineering and Industrial Aerodynamics* 142:149-163.

Balslev YJ, Potchter O, Matzarakis A (2015) Climatic and thermal comfort analysis of the Tel-Aviv Geddes Plan: A historical perspective. *Building and Environment* 93, Part 2:302-318.

Banks R, Tiana-Alsina J, Rocadenbosch F, Baldasano J (2015) Performance Evaluation of the Boundary-Layer Height from Lidar and the Weather Research and Forecasting Model at an Urban Coastal Site in the North-East Iberian Peninsula. *Boundary-Layer Meteorology* 157:265-292.

Bechtel B, Schmidt KJ (2011) Floristic mapping data as a proxy for the mean urban heat island. *Climate Research* 49:45-58.

Behzadian K, Kapelan Z (2015) Advantages of integrated and sustainability based assessment for metabolism based strategic planning of urban water systems. *Science of The Total Environment* 527–528:220-231.

Bernabe A, Bernard J, Musy M, Andrieu H, Bocher E, Calmet I, Keravec P, Rosant JM (2015) Radiative and heat storage properties of the urban fabric derived from analysis of surface forms. *Urban Climate* 12:205-218.

Bian T, Ren G, Zhang B, Zhang L, Yue Y (2015) Urbanization effect on long-term trends of extreme temperature indices at Shijiazhuang station, North China. *Theoretical and Applied Climatology* 119(3):407-418.

Bokwa A, Hajto MJ, Walawender JP, Szymanowski M (2015) Influence of diversified relief on the urban heat island in the city of Kraków, Poland. *Theoretical and Applied Climatology* 122(1):365-382.

Bradley S, Barlow J, Lalley J, Halois C (2015) A sodar for profiling in a spatially inhomogeneous urban environment. *Meteorologische Zeitschrift* 24:615-624.

Brown C, Lundholm J (2015) Microclimate and substrate depth influence green roof plant community dynamics. *Landscape and Urban Planning* 143:134-142.

Buccolieri R, Salizzoni P, Soulhac L, Garbero V, Sabatino SD (2015) The breathability of compact cities. *Urban Climate* 13:73-93.

Buchholz S, Kossmann M (2015) Research note. Visualisation of summer heat intensity for different settlement types and varying surface fraction partitioning. *Landscape and Urban Planning* 144:59-64.

Burton A, Bambrick H, Friel S (2015) If you don't know how can you plan? Considering the health impacts of climate change in urban planning in Australia. *Urban Climate* 12:104-118.

Carpentieri M, Robins AG (2015) Influence of urban morphology on air flow over building arrays. *Journal of Wind Engineering and Industrial Aerodynamics* 145:61-74.

Castiñeira-Ibañez S, Rubio C, Sánchez-Pérez JV (2015) Environmental noise control during its transmission phase to protect buildings. Design model for acoustic barriers based on arrays of isolated scatterers. *Building and Environment* 93, Part 2:179-185.

Chapman L, Muller CL, Young DT, Warren EL, Grimmond CSB, Cai XM, Ferranti EJS (2015) The Birmingham Urban Climate Laboratory: An Open Meteorological Test Bed and Challenges of the Smart City. *Bulletin of the American Meteorological Society* 96:1545-1560.

Chen G, Zhu X, Sha W, Iwasaki T, Seko H, Saito K, Iwai H, Ishii S (2015) Toward Improved Forecasts of Sea-Breeze Horizontal Convective Rolls at Super High Resolutions. Part II: The Impacts of Land Use and Buildings. *Monthly Weather Review* 143:1873-1894.

Chen Z, Yin L, Chen X, Wei S, Zhu Z (2015) Research on the characteristics of urban rainstorm pattern in the humid area of Southern China: a case study of Guangzhou City. *International Journal of Climatology* 35:4370-4386.

Chung J, Hagishima A, Ikegaya N, Tanimoto J (2015) Wind-Tunnel Study of Scalar Transfer Phenomena for Surfaces of Block Arrays and Smooth Walls with Dry Patches. *Boundary-Layer Meteorology* 157:219-236.

Colunga MI, Cambron-Sandoval VH, Suzan-Azpiri H, Guevara-Escobar A, Luna-Soria H (2015) The role of urban vegetation in temperature and heat island effects in Queretaro city, Mexico. *Atmosfera* 28:205-218.

Comber A, Brunsdon C (2015) A spatial analysis of plant phenophase changes and the impact of increases in urban land use. *International Journal of Climatology* 35:972-980.

Corumluoglu O, Asri I (2015) The effect of urban heat island on Izmir's city ecosystem and climate. *Environmental Science and Pollution Research* 22(5):3202-3211.

Crawford B, Christen A (2015) Spatial source attribution of measured urban eddy covariance CO2 fluxes. *Theoretical and Applied Climatology* 119(3):733-755.

Cui E, Ren L, Sun H (2015) Evaluation of variations and affecting factors of eco-environmental quality during urbanization. *Environmental Science and Pollution Research* 22(5):3958-3968.

Ding Z, Guo P, Xie F, Chu H, Li K, Pu J, Pang S, Dong H, Liu Y, Pi F, Zhang Q (2015) Impact of diurnal temperature range on mortality in a high plateau area in southwest China: A time series analysis. *Science of The Total Environment* 526:358-365.

Ezber Y, Sen OL, Boybeyi Z, Karaca M (2015) Investigation of local flow features in Istanbul. Part II: high-resolution real case simulations. *International Journal of Climatology* 35:4802-4828.

Fantozzi F, Monaci F, Blanusa T, Bargagli R (2015) Spatio-temporal variations of ozone and nitrogen dioxide concentrations under urban trees and in a nearby open area. *Urban Climate* 12:119-27.

Farnham C, Emura K, Mizuno T (2015) Evaluation of cooling effects: outdoor water mist fan. *Building Research and Information* 43:334-345.

Garcia-Escalante JS, Garcia-Reynoso JA, Jazcilevich-Diamant A, Ruiz-Suarez LG (2014) The influence of the Tula, Hidalgo complex on the air quality of the Mexico City Metropolitan Area. *Atmosfera* 27:215-225.

García-Nieto PJ, Álvarez-Antón JC, Vilán-Vilán JA, García-Gonzalo E (2015) Air quality modeling in the Oviedo urban area (NW Spain) by using multivariate adaptive regression splines. *Environmental Science and Pollution Research* 22(9):6642-6659.

Gavilan PM, Pincheira-Ulbrich J, Rojo F (2013) Climate change and its effects on urban spaces in Chile: A summary of research carried out in the period 2000-2012. *Atmosfera* 26:547-566.

Ge H (2015) Influence of time resolution and averaging techniques of meteorological data on the estimation of wind-driven rain load on building facades for Canadian climates. *Journal of Wind Engineering and Industrial Aerodynamics* 143:50-61.

Ghannam K, Poggi D, Porporato A, Katul G (2015) The Spatio-temporal Statistical Structure and Ergodic Behaviour of Scalar Turbulence Within a Rod Canopy. *Boundary-Layer Meteorology* 157:447-460.

Ghassoun Y, Ruths M, Lцwner M-O, Weber S (2015) Intra-urban variation of ultrafine particles as evaluated by process related land use and pollutant driven regression modelling. *Science of The Total Environment* 536:150-160.

Guindon S-M, Nirupama N (2015) Reducting risk from urban heat island effects in cities. *Natural Hazards* 77:823-831.

Guo W, Lu D, Wu Y, Zhang J (2015) Mapping Impervious Surface Distribution with Integration of SNNP VIIRS-DNB and MODIS NDVI Data. *Remote Sensing* 7:12459.

Gutierrez E, Martilli A, Santiago J, González J (2015) A Mechanical Drag Coefficient Formulation and Urban Canopy Parameter Assimilation Technique for Complex Urban Environments. *Boundary-Layer Meteorology* 157:333-341.

Haas J, Furberg D, Ban Y (2015) Satellite monitoring of urbanization and environmental impacts—A comparison of Stockholm and Shanghai. *International Journal of Applied Earth Observation and Geoinformation* 38:138-149.

Habeeb D, Vargo J, Stone Brian J (2015) Rising heat wave trends in large US cities. *Natural Hazards* 76:1651-1665.

Hamdi R, Giot O, Troch RD, Deckmyn A, Termonia P (2015) Future climate of Brussels and Paris for the 2050s under the A1B scenario. *Urban Climate* 12:160-182.

He C, Zhao Y, Huang Q, Zhang Q, Zhang D (2015) Alternative future analysis for assessing the potential impact of climate change on urban landscape dynamics. *Science of The Total Environment* 532:48-60.

He Y, Ai B, Yao Y, Zhong F (2015) Deriving urban dynamic evolution rules from self-adaptive cellular automata with multi-temporal remote sensing images. *International Journal of Applied Earth Observation and Geoinformation* 38:164-174.

Heaviside C, Cai X-M, Vardoulakis S (2015) The effects of horizontal advection on the urban heat island in Birmingham and the West Midlands, United Kingdom during a heatwave. *Quarterly Journal of the Royal Meteorological Society* 141:1429-1441.

Hellsten A, Luukkonen S-M, Steinfeld G, Kanani-Sühring F, Markkanen T, Järvi L, Lento J, Vesala T, Raasch S (2015) Footprint Evaluation for Flux and Concentration Measurements for an Urban-Like Canopy with Coupled Lagrangian Stochastic and Large-Eddy Simulation Models. *Boundary-Layer Meteorology* 157:191-217.

Her Y, Chaubey I (2015) Impact of the numbers of observations and calibration parameters on equifinality, model performance, and output and parameter uncertainty. *Hydrological Processes* 29:4220-4237.

Hondula D, Davis R (2014) The predictability of high-risk zones for heat-related mortality in seven US cities. *Natural Hazards* 74:771-788.

Hu S, Tong L, Frazier AE, Liu Y (2015) Urban boundary extraction and sprawl analysis using Landsat images: A case study in Wuhan, China. *Habitat International* 47:183-195.

Huang C, Zhang M, Zou J, Zhu A-x, Chen X, Mi Y, Wang Y, Yang H, Li Y (2015) Changes in land use, climate and the environment during a period of rapid economic development in Jiangsu Province, China. *Science of The Total Environment* 536:173-181.

Ikram M, Yan Z, Liu Y, Qu W (2015) Seasonal effects of temperature fluctuations on air quality and respiratory disease: a study in Beijing. *Natural Hazards* 79:833-853.

Jesson M, Sterling M, Letchford C, Baker C (2015) Aerodynamic forces on the roofs of low-, mid- and high-rise buildings subject to transient winds. *Journal of Wind Engineering and Industrial Aerodynamics* 143:42-49.

Jiménez E., Tapiador FJ, Sáez-Martínez FJ (2015) Atmospheric pollutants in a changing environment: key issues in reactivity and monitoring, global warming, and health. *Environmental Science and Pollution Research* 22(7):4789-4792.

Jing W, Yang Y, Yue X, Zhao X (2015) Mapping Urban Areas with Integration of DMSP/OLS Nighttime Light and MODIS Data Using Machine Learning Techniques. *Remote Sensing* 7:12419.

Johann FA, Carlos ME, Ricardo FL (2015) Wind-induced motion on tall buildings: A comfort criteria overview. *Journal of Wind Engineering and Industrial Aerodynamics* 142:26-42.

Jokar-Arsanjani J, Vaz E (2015) An assessment of a collaborative mapping approach for exploring land use patterns for several European metropolises. *International Journal of Applied Earth Observation and Geoinformation* 35 Part B:329-337.

Kaźmierczak B, Kotowski A (2014) The influence of precipitation intensity growth on the urban drainage systems designing. *Theoretical and Applied Climatology* 118(1):285-296.

Kim W, Tamura Y, Yoshida A (2015) Interference effects on aerodynamic wind forces between two buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 147:186-201.

Kim YC, Tamura Y, won Yoon S (2015) Proximity effect on low-rise building surrounded by similar-sized buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 146:150-162.

Knippertz P, Evans MJ, Field PR, Fink AH, Liousse C, Marsham JH (2015) The possible role of local air pollution in climate change in West Africa. *Nature Climate Change* 5:815-822.

Kolokotsa D, Santamouris M (2015) Review of the indoor environmental quality and energy consumption studies for low income households in Europe. *Science of The Total Environment* 536:316-330.

Koopmans S, Theeuwes NE, Steeneveld GJ, Holtslag AAM (2015) Modelling the influence of urbanization on the 20th century temperature record of weather station De Bilt (The Netherlands). *International Journal of Climatology* 35:1732-1748.

Kruger E, Drach P, Brode P (2015) Implications of air-conditioning use on thermal perception in open spaces: A field study in downtown Rio de Janeiro. *Building and Environment* 94, Part 1:417-425.

Kubilay A, Derome D, Blocken B, Carmeliet J (2015) Wind-driven rain on two parallel wide buildings: Field measurements and CFD simulations. *Journal of Wind Engineering and Industrial Aerodynamics* 146:11-28.

Kumar L, Taylor S (2015) Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change* 5: 992–996.

Kumar R, Kumari KM (2015) Aerosols and trace gases characterization over Indo-Gangetic plain in semiarid region. *Urban Climate* 12:11-20.

Kurppa M, Nordbo A, Haapanala S, Jarvi L (2015) Effect of seasonal variability and land use on particle number and CO2 exchange in Helsinki, Finland. *Urban Climate* 13:94-109.

Lee TW, Ho A (2010) Scaling of the urban heat island effect based on the energy balance: nighttime minimum temperature increase vs. urban area length scale. *Climate Research* 42:209-216.

Lee W (2014) Historical global analysis of occurrences and human casualty of extreme temperature events (ETEs). *Natural Hazards* 70:1453-1505.

Lehnert M, Geletič J, Husák J, Vysoudil M (2015) Urban field classification by “local climate zones” in a medium-sized Central European city: the case of Olomouc (Czech Republic). *Theoretical and Applied Climatology* 122(3):531-541.

Lelovics E, Unger J, Gal T, Gal CV (2014) Design of an urban monitoring network based on Local Climate Zone mapping and temperature pattern modelling. *Climate Research* 60:51-62.

Li L, Chan PW, Wang D, Tan M (2015) Rapid urbanization effect on local climate: intercomparison of climate trends in Shenzhen and Hong Kong, 1968-2013. *Climate Research* 63:145-155.

Li Y-C, Cheng C-M, Lo Y-L, Fang F-M, qian Zheng D (2015) Simulation of turbulent flows around a prism in suburban terrain inflow based on random flow generation method simulation. *Journal of Wind Engineering and Industrial Aerodynamics* 146:51-58.

Lietzke B, Vogt R, Feigenwinter C, Parlow E (2015) On the controlling factors for the variability of carbon dioxide flux in a heterogeneous urban environment. *International Journal of Climatology* 35:3921-3941.

Lindberg F, Grimmond CSB (2010) Continuous sky view factor maps from high resolution urban digital elevation models. *Climate Research* 42:177-183.

Lindberg F, Grimmond CSB, Martilli A (2015) Sunlit fractions on urban facets - Impact of spatial resolution and approach. *Urban Climate* 12:65-84.

Liu G, Zhang L, He B, Jin X, Zhang Q, Razafindrabe B, You H (2015) Temporal changes in extreme high temperature, heat waves and relevant disasters in Nanjing metropolitan region, China. *Natural Hazards* 76:1415-1430.

Liu Z, Hu B, Wang L, Wu F, Gao W, Wang Y (2015) Seasonal and diurnal variation in particulate matter (PM10 and PM2.5) at an urban site of Beijing: analyses from a 9-year study. *Environmental Science and Pollution Research* 22(1):627-642.

Liu Z, Ishihara T (2015) A study of tornado induced mean aerodynamic forces on a gable-roofed building by the large eddy simulations. *Journal of Wind Engineering and Industrial Aerodynamics* 146:39-50.

Lokoshchenko MA, Korneva IA (2015) Underground urban heat island below Moscow city. *Urban Climate* 13:1-13.

Lopez-Espinoza ED, Zavala-Hidalgo J, Gomez-Ramos O (2012) Weather forecast sensitivity to changes in urban land covers using the WRF model for central Mexico. *Atmosfera* 25:127-154.

Loupa G, Rapsomanikis S, Trepekli A, Kourtidis K (2016) Energy flux parametrization as an opportunity to get Urban Heat Island insights: The case of Athens, Greece (Thermopolis 2009 Campaign). *Science of The Total Environment* 542, Part A:136-143.

Ma J, Liu Z, Chai Y (2015) The impact of urban form on CO2 emission from work and non-work trips: The case of Beijing, China. *Habitat International* 47:1-10.

Mackintosh TJ, Davis JA, Thompson RM (2015) The influence of urbanisation on macroinvertebrate biodiversity in constructed stormwater wetlands. *Science of The Total Environment* 536:527-537.

Maimaitijiang M, Ghulam A.and Onésimo-Sandoval J, Maimaitiyiming M (2015) Drivers of land cover and land use changes in St. Louis metropolitan area over the past 40 years characterized by remote sensing and census population data. *International Journal of Applied Earth Observation and Geoinformation* 35 Part B:161-174.

Mavrakis A, Papavasileiou C, Salvati L (2015) Towards (Un)sustainable urban growth? Industrial development, land-use, soil depletion and climate aridity in a Greek agro-forest area. *Journal of Arid Environments* 121:1-6.

Mavrogianni A, Taylor J, Davies M, Thoua C, Kolm-Murray J (2015) Urban social housing resilience to excess summer heat. *Building Research and Information* 43:316-333.

Mavromatidis G, Orehounig K, Carmeliet J (2015) Evaluation of photovoltaic integration potential in a village. *Solar Energy* 121:152-168.

Middel A, Brazel AJ, Kaplan S, Myint SW (2012) Daytime cooling efficiency and diurnal energy balance in Phoenix, Arizona, USA. *Climate Research* 54:21-34.

Mohammad AF, Zaki SA, Hagishima A, Ali MSM (2015) Determination of aerodynamic parameters of urban surfaces: methods and results revisited. *Theoretical and Applied Climatology* 122(3):635-649.

Molenaar RE, Heusinkveld BG, Steeneveld GJ (2015) Projection of rural and urban human thermal comfort in The Netherlands for 2050. *International Journal of Climatology* doi:10.1002/joc.4453.

Montazeri H, Blocken B, Derome D, Carmeliet J, Hensen J (2015) CFD analysis of forced convective heat transfer coefficients at windward building facades: Influence of building geometry. *Journal of Wind Engineering and Industrial Aerodynamics* 146:102-116.

Montelongo-Reyes MM, Otazo-Sánchez EM, Romo-Gómez C, Gordillo-Martinez AJ, Galindo-Castillo E (2015) GHG and black carbon emission inventories from Mezquital Valley: The main energy provider for Mexico Megacity. *Science of The Total Environment* 527–528:455-464.

Moreno T, Reche C, Rivas I, Cruz Minguillon M, Martins V, Vargas C, Buonanno G, Parga J, Pandolfi M, Brines M, Ealo M, Sofia Fonseca A, Amato F, Sosa G, Capdevila M, de Miguel E, Querol X, Gibbons W (2015) Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona. *Environmental Research* 142:495-510.

Moustris KP, Nastos PT, Bartzokas A, Larissi IK, Zacharia PT, Paliatsos AG (2015) Energy consumption based on heating/cooling degree days within the urban environment of Athens, Greece. *Theoretical and Applied Climatology* 122(3):517-529.

Muis S, Güneralp B, Jongman B, Aerts JCJH, Ward PJ (2015) Flood risk and adaptation strategies under climate change and urban expansion: A probabilistic analysis using global data. *Science of The Total Environment* 538:445-457.

Muller C, Chapman L, Johnston S, Kidd C, Illingworth S, Foody G, Overeem A, Leigh R (2015) Crowdsourcing for climate and atmospheric sciences: current status and future potential. *International Journal of Climatology* 35:3185-3203.

Nazarian N, Kleissl J (2015) CFD simulation of an idealized urban environment: Thermal effects of geometrical characteristics and surface materials. *Urban Climate* 12:141-159.

Nordbo A, Karsisto P, Matikainen L, Wood CR, Jarvi L (2015) Urban surface cover determined with airborne lidar at 2 m resolution – Implications for surface energy balance modelling. *Urban Climate* 13:52-72.

Okaze T, Ono A, Mochida A, Kannuki Y, Watanabe S (2015) Evaluation of turbulent length scale within urban canopy layer based on LES data. *Journal of Wind Engineering and Industrial Aerodynamics* 144:79-83.

Onur AC, Tezer A (2015) Ecosystem services based spatial planning decision making for adaptation to climate changes. *Habitat International* 47:267-278.

Owrangi A, Lannigan R, Simonovic S (2014) Interaction between land-use change, flooding and human health in Metro Vancouver, Canada. *Natural Hazards* 72:1219-1230.

Pandey AK, Pandey M, Mishra A, Tiwary SM, Tripathi BD (2015) Air pollution tolerance index and anticipated performance index of some plant species for development of urban forest. *Urban Forestry & Urban Greening* 14:866-871.

Papamanolis N (2015) The main characteristics of the urban climate and the air quality in Greek cities. *Urban Climate* 12:49-64.

Patel NN, Angiuli E, Gamba P, Gaughan A, Lisini G, Stevens FR, Tatem AJ, Trianni G (2015) Multitemporal settlement and population mapping from Landsat using Google Earth Engine. *International Journal of Applied Earth Observation and Geoinformation* 35 Part B:199-208.

Peña J, Aran M, Raso J, Pérez-Zanón N (2015) Principal sequence pattern analysis of episodes of excess mortality due to heat in the Barcelona metropolitan area. *International Journal of Biometeorology* 59:435-446.

Peng LLH, Jim CY (2015) Economic evaluation of green-roof environmental benefits in the context of climate change: The case of Hong Kong. *Urban Forestry & Urban Greening* 14:554-561.

Petralli M, Brandani G, Napoli M, Messeri A, Massetti L (2015) Thermal comfort and green areas in Florence. *Italian Journal of Agrometeorology* 20(2):39-48.

Poursanidis D, Chrysoulakis N, Mitraka Z (2015) Landsat 8 vs. Landsat 5: A comparison based on urban and peri-urban land cover mapping. *International Journal of Applied Earth Observation and Geoinformation* 35 Part B:259-269.

Prashar S, Shaw R, Takeuchi Y (2012) Assessing the resilience of Delhi to climate-related disasters: a comprehensive approach. *Natural Hazards* 64:1609-1624.

Progiou AG, Ziomas IC (2015) Predicting annual average particulate concentration in urban areas. *Science of The Total Environment* 532:353-359.

Qaid A, Ossen DR, Jamei E, Manaf N. A., Said I., Hamdan MA (2015) Urban surface temperature behaviour and heat island effect in a tropical planned city. *Theoretical and Applied Climatology* 119(3):493-514.

Ramamurthy P, Pardyjak E (2015) Turbulent transport of carbon dioxide over a highly vegetated suburban neighbourhood. *Boundary-Layer Meteorology* 157:461-479.

Ramamurthy P, Sun T, Rule K, Bou-Zeid E (2015) The joint influence of albedo and insulation on roof performance: An observational study. *Energy and Buildings* 93:249-258.

Ramamurthy P, Sun T, Rule K, Bou-Zeid E (2015) The joint influence of albedo and insulation on roof performance: A modeling study. *Energy and Buildings* 102:317-327.

Rayner D, Lindberg F, Thorsson S, Holmer B (2015) A statistical downscaling algorithm for thermal comfort applications. *Theoretical and Applied Climatology* 122(3):729-742.

Ren L, Cui E, H. S (2014) Temporal and spatial variations in the relationship between urbanization and water quality. *Environmental Science and Pollution Research* 21(23):13646-13655.

Ren P, Meng Q, Zhang Y, Zhao L, Yuan X, Feng X (2015) An Unmanned Airship Thermal Infrared Remote Sensing System for Low-Altitude and High Spatial Resolution Monitoring of Urban Thermal Environments: Integration and an Experiment. *Remote Sensing* 7:14259-14275.

Rhea L, Jarnagin T, Hogan D, Loperfido JV, Shuster W (2015) Effects of urbanization and stormwater control measures on streamflows in the vicinity of Clarksburg, Maryland, USA. *Hydrological Processes* 29:4413-4426.

Ridder KD, Lauwaet D, Maiheu B (2015) UrbClim - A fast urban boundary layer climate model. *Urban Climate* 12:21-48.

Rossi F, Anderini E, Castellani B, Nicolini A, Morini E (2015) Integrated improvement of occupants' comfort in urban areas during outdoor events. *Building and Environment* 93, Part 2:285-292.

Ruiz MA, Correa EN (2015) Suitability of different comfort indices for the prediction of thermal conditions in tree-covered outdoor spaces in arid cities. *Theoretical and Applied Climatology* 122(1):69-83.

Rupprecht CDD, Byrne JA, Garden JG, Hero J-M (2015) Informal urban green space: A trilingual systematic review of its role for biodiversity and trends in the literature. *Urban Forestry & Urban Greening* 14:883-908.

Salim MH, Schlünzen KH, Grawe D (2015) Including trees in the numerical simulations of the wind flow in urban areas: Should we care? *Journal of Wind Engineering and Industrial Aerodynamics* 144:84-95.

Samsonov TE, Konstantinov PI, Varentsov MI (2015) Object-oriented approach to urban canyon analysis and its applications in meteorological modeling. *Urban Climate* 13:122-139.

Savić S, Selakov A, Milošević D (2014) Cold and warm air temperature spells during the winter and summer seasons and their impact on energy consumption in urban areas. *Natural Hazards* 73:373-387.

Shafizadeh-Moghadam H, Helbich M (2015) Spatiotemporal variability of urban growth factors: A global and local perspective on the megacity of Mumbai. *International Journal of Applied Earth Observation and Geoinformation* 35 Part

B:187-198.

Son J-Y, Kim H, Bell ML (2015) Does urban land-use increase risk of asthma symptoms? *Environmental Research* 142:309-318.

de Souza DO, dos Santos Alvalá RC, do Nascimento MG (2016) Urbanization effects on the microclimate of Manaus: A modeling study. *Atmospheric Research* 167:237-248.

Suomi J, Hjort J, Kayhko J (2012) Effects of scale on modelling the urban heat island in Turku, SW Finland. *Climate Research* 55:105-118.

Swoczyna T, Kalaji HM, Pietkiewicz S, Borowski J (2015) Ability of various tree species to acclimation in urban environments probed with the JIP-test. *Urban Forestry & Urban Greening* 14:544-553.

Takane Y, Kusaka H, Kondo H (2015) Investigation of a recent extreme high-temperature event in the Tokyo metropolitan area using numerical simulations: the potential role of a 'hybrid' foehn wind. *Quarterly Journal of the Royal Meteorological Society* 141:1857-1869.

Takebayashi H, Ishii E, Moriyama M, Sakaki A, Nakajima S, Ueda H (2015) Study to examine the potential for solar energy utilization based on the relationship between urban morphology and solar radiation gain on building rooftops and wall surfaces. *Solar Energy* 119:362-369.

Tam BY, Gough WA, Mohsin T (2015) The impact of urbanization and the urban heat island effect on day to day temperature variation. *Urban Climate* 12:1-10.

Tan M, Li X (2015) Quantifying the effects of settlement size on urban heat islands in fairly uniform geographic areas. *Habitat International* 49:100-106.

Tavakoli M, De Smedt F, Vansteenkiste T, Willems P (2014) Impact of climate change and urban development on extreme flows in the Grote Nete watershed, Belgium. Natural Hazards 71:2127-2142.

Tejeda-Martinez A, Luyando E, Jauregui E (2011) Average conditions of thermal stress in Mexican cities with more than one million inhabitants in the face of climatic change. *Atmosfera* 24:15-30.

Toja-Silva F, Peralta C, Lopez-Garcia O, Navarro J, Cruz I (2015) Effect of roof-mounted solar panels on the wind energy exploitation on high-rise buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 145:123-138.

Toja-Silva F, Peralta C, Lopez-Garcia O, Navarro J, Cruz I (2015) Roof region dependent wind potential assessment with different RANS turbulence models. *Journal of Wind Engineering and Industrial Aerodynamics* 142:258-271.

Tominaga Y (2015) Flow around a high-rise building using steady and unsteady RANS CFD: Effect of large-scale fluctuations on the velocity statistics. *Journal of Wind Engineering and Industrial Aerodynamics* 142:93-103.

Tong S, FitzGerald G, Wang X-Y, Aitken P, Tippett V, Chen D, Wang X, Guo Y (2015) Exploration of the health risk-based definition for heatwave: A multi-city study. *Environmental Research* 142:696-702.

Torres-Valcárcel ÁR, Harbor J, Torres-Valcárcel AL, González-Avilés CJ (2015) Historical differences in temperature between urban and non-urban areas in Puerto Rico. *International Journal of Climatology* 35:1648-1661.

Tsegas G, Moussiopoulos N, Barmpas F, Akylas V, Douros I (2015) An integrated numerical methodology for describing multiscale interactions on atmospheric flow and pollutant dispersion in the urban atmospheric boundary layer. *Journal of Wind Engineering and Industrial Aerodynamics* 144:191-201.

Turker M, Koc-San D (2015) Building extraction from high-resolution optical spaceborne images using the integration of support vector machine (SVM) classification, Hough transformation and perceptual grouping. *International Journal of Applied Earth Observation and Geoinformation* 34:58-69.

Vernay DG, Raphael B, Smith IF (2015) A model-based data-interpretation framework for improving wind predictions around buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 145:219-228.

Vranckx S, Vos P, Maiheu B, Janssen S (2015) Impact of trees on pollutant dispersion in street canyons: A numerical study of the annual average effects in Antwerp, Belgium. *Science of The Total Environment* 532:474-483.

Wang H, Hou X, Deng Y (2015) Numerical simulations of wind-driven rain on building facades under various oblique winds based on Eulerian multiphase model. *Journal of Wind Engineering and Industrial Aerodynamics* 142:82-92.

Wang X, Huang G, Liu J (2015) Projected increases in near-surface air temperature over Ontario, Canada: a regional climate modeling approach. *Climate Dynamics* 45:1381-93.

Wang X, Sun X, Tang J, Yang X (2015) Urbanization-induced regional warming in Yangtze River Delta: potential role of anthropogenic heat release. *International Journal of Climatology* 35:4417-4430.

Wang Y, Zhang L, Takis-Mathiopoulos P, Deng H (2015) A Gestalt rules and graph-cut-based simplification framework for urban building models. *International Journal of Applied Earth Observation and Geoinformation* 35 Part B:247-258.

Wen J-c, Lee Y-j, Cheng S-j, Lee J-h (2014) Changes of rural to urban areas in hydrograph characteristics on watershed divisions. *Natural Hazards* 74:887-909.

Wong GK, Jim C (2015) Identifying keystone meteorological factors of green-roof stormwater retention to inform design and planning. *Landscape and Urban Planning* 143:173-182.

Xu G, Guo P, Li X, Jia Y (2015) Seasonal forecasting of 2014 summer heat wave over Beijing using GRAAP and other statistical methods. Natural Hazards 75:1909-1925.

Xu T, Lv Y, Cheng T, X. L (2015) Using comprehensive GC × GC to study PAHs and n-alkanes associated with PM2.5 in urban atmosphere. *Environmental Science and Pollution Research* 22(7):5253-5262.

Yan X, Wang H, Hou Z, Wang S, Zhang D, Xu Q, Tokola T (2015) Spatial analysis of the ecological effects of negative air ions in urban vegetated areas: A case study in Maiji, China. *Urban Forestry & Urban Greening* 14:636-645.

Yang F, Lau SSY, F. Q (2015) Cooling performance of residential greenery in localised urban climates: a case study in Shanghai China. *International Journal of Environmental Technology and Management* 18(5-6):478-503.

Yang J, He Y, Caspersen J (2015) Fully constrained linear spectral unmixing based global shadow compensation for high resolution satellite imagery of urban areas. *International Journal of Applied Earth Observation and Geoinformation* 38. DOI: 10.1016/j.jag.2014.12.005.

Yang J, Wong MS, Menenti M, Nichol J (2015) Study of the geometry effect on land surface temperature retrieval in urban environment. *ISPRS Journal of Photogrammetry and Remote Sensing* 109:77-87.

Yang L, Tian F, Niyogi D (2015) A need to revisit hydrologic responses to urbanization by incorporating the feedback on spatial rainfall patterns. *Urban Climate* 12:128-140.

Yao F, Wang C, Dong D, Luo J, Shen Z, Yang K (2015) High-Resolution Mapping of Urban Surface Water Using ZY-3 Multi-Spectral Imagery. *Remote Sensing* 7(9):12336-12355.

Yu X, Ma J, Kumar KR, Zhu B, An J, He J, Li M (2016) Measurement and analysis of surface aerosol optical properties over urban Nanjing in the Chinese Yangtze River Delta. *Science of The Total Environment* 542, Part A:277-291.

Yubero E, Galindo N, Nicolás JF, Crespo J, Calzolai G, Lucarelli F (2015) Temporal variations of PM1 major components in an urban street canyon. *Environmental Science and Pollution Research* 22(17):13328-13335.

Zeiger S, Hubbart JA (2016) Quantifying suspended sediment flux in a mixed-land-use urbanizing watershed using a nested-scale study design. *Science of The Total Environment* 542, Part A:315-323.

Zeng C, Liu Y, Stein A, Jiao L (2015) Characterization and spatial modeling of urban sprawl in the Wuhan Metropolitan Area, China. *International Journal of Applied Earth Observation and Geoinformation* 34:10–24.

Zhang C, Chen Y, Lu D (2015) Mapping the land-cover distribution in arid and semiarid urban landscapes with Landsat Thematic Mapper imagery. *International Journal of Remote Sensing* 36:4483-4500.

Zhang Q, Li B, Thau D, Moore R (2015) Building a Better Urban Picture: Combining Day and Night Remote Sensing Imagery. *Remote Sensing* 7:11887.

Zhang Q, Miao L, Wang X, Liu D, Zhu L, Zhou B, Sun J, Liu J (2015) The capacity of greening roof to reduce stormwater runoff and pollution. *Landscape and Urban Planning* 144:142-150.

Zhang X, Xia X, Xuan C (2015) On the drivers of variability and trend of surface solar radiation in Beijing metropolitan area. *International Journal of Climatology* 35:452-461.

Zhang Y, Balzter H, Zou C, Xu H, Tang F (2015) Characterizing bi-temporal patterns of land surface temperature using landscape metrics based on sub-pixel classifications from Landsat TM/ETM. *International Journal of Applied Earth Observation and Geoinformation* 42:87-96.

Zhao Q, Myint SW, Wentz EA, Fan C (2015) Rooftop Surface Temperature Analysis in an Urban Residential Environment. *Remote Sensing* 7:12135-12159.

Zheng Z, Qi S, Xu Y (2013) Questionable frequent occurrence of urban flood hazards in modern cities of China. *Natural Hazards* 65:1009-1010.

Zhou G, Singh J, Wu J, Sinha R, Laurenti R, Frostell B (2015) Evaluating low-carbon city initiatives from the DPSIR framework perspective. *Habitat International* 50:289-299.

Živojinović I, Wolfslehner B (2015) Perceptions of urban forestry stakeholders about climate change adaptation – A Q-method application in Serbia. *Urban Forestry & Urban Greening* 14:1079-1087.

Zou B, Wang M. and Wan N, Gaines-Wilson J, Fang X, Y. T (2015) Spatial modeling of PM2.5 concentrations with a multifactoral radial basis function neural network. *Environmental Science and Pollution Research* 22(14):10395-10404.

Upcoming Conferences...

INTERNATIONAL WINTER CITIES SYMPOSIUM (IWCS 2016)
Erzurum, Turkey • February 10-12, 2016*
http://wintercities2016.atauni.edu.tr/eng/

INTERNATIONAL CONFERENCE ON COUNTER-MEASURES TO URBAN HEAT ISLANDS
NUS, Singapore • May 30-June 1, 2016
http://www.ic2uhi2016.org/

EMERGING URBAN DYNAMICS AND FUTURE SUSTAINABLE CLIMATES OF ASIAN CITIES: A PANEL SESSION AT THE AAG ANNUAL MEETING
San Francisco CA, USA • March 29 – April 2, 2016
http://www.aag.org/annualmeeting

Organizers: Dr. Winston Chow, National University of Singapore (winstonchow@nus.edu.sg) and Dr. Chandana Mitra, Auburn University (chandana@auburn.edu)

A 'Working Group' on Protocols for the Assessment and Reporting of Outdoor Thermal Comfort

Some members of the IAUC have been toying with the idea of developing a standardized regime of assessment and reporting of outdoor thermal comfort for a while. An initial discussion on forming a 'Working Group' was discussed on 21 July 2015 in Toulouse, on the sidelines of ICUC9.

The purpose of the group is to:

(a) develop standards/protocols for the proper conduct of outdoor thermal comfort studies

(b) carry out new outdoor thermal comfort studies using (a) above, in regions that currently do not have adequate studies

(c) inter-compare results of 'standard' outdoor thermal comfort studies

(d) publish results

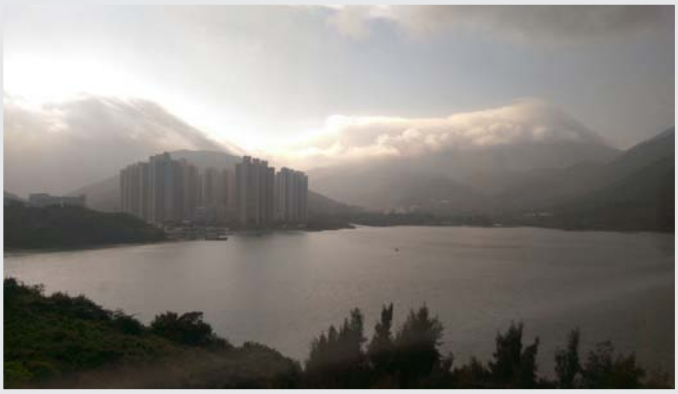
Standards and protocols related to several aspects of outdoor thermal comfort measurement are essential to the above purpose, including sample selection, questionnaire, time of survey, instrumentation and especially the Mean Radiant Temperature (MRT). Johansson et al., (2014) provide a useful starting point in this regard.

We would now like to widen the membership of our 'Group' to fulfill the above purposes and this news item serves as a call to interested members to join the initiative. Please join us to both standardize the measurement and reporting of outdoor comfort as well as to create a more representative and high quality database of outdoor comfort studies from around the world.

If you are interested, please drop me an email at: Rohinton.Emmanuel@gcu.ac.uk.

— Rohinton Emmanuel

Reference: Johansson E, Thorsson S, Emmanuel R, Krüger E. (2014) Instruments and methods in outdoor thermal comfort studies – The need for standardization, *Urban Climate*, 10(2), pp. 346-366.



Hong Kong, December 2015 (Photo: D. Pearlmutter)

Board Members & Terms

- Tim Oke (Univ. of British Columbia, Canada): President, 2000-2003; Past President, 2003-2006; Emeritus President 2007-2009*
- Sue Grimmond (King's College London, UK): 2000-2003; President, 2003-2007; Past President, 2007-2009*
- Matthias Roth (National University of Singapore, Singapore): 2000-2003; Secretary, 2003-2007; Acting-Treasurer 2006; President, 2007-2009; Past President, 2009-2011*
- Gerald Mills (UCD, Dublin, Ireland): 2007-2011; President, 2009-2013; Past President, 2014-
- James Voogt (University of Western Ontario, Canada), 2000-2006; Webmaster 2007-2013; President, 2014-
- Andreas Christen (University of British Columbia, Canada): 2012-2016
- Rohinton Emmanuel (Glasgow Caledonian University, UK): 2006-2010; Secretary, 2009-2013
- Jason Ching (EPA Atmospheric Modelling & Analysis Division, USA): 2009-2013*
- David Pearlmutter (Ben-Gurion University of the Negev, Israel): Newsletter Editor, 2009-*
- Aude Lemonsu (CNRS, France): 2010-2014; ICUC-9 Local Organizer, 2014-2015*
- David Sailor (Portland State University, USA): 2011-2015; Secretary, 2014-
- Alexander Baklanov (University of Copenhagen): 2013-2017
- Curtis Wood (Finnish Meteorological Inst., Finland): 2013-2017
- Valéry Masson (Météo France, France): ICUC-9 Local Organizer, 2014-2015*
- Fei Chen (NCAR, USA): 2014-2018
- Edward Ng (Chinese University of Hong Kong, Hong Kong): 2014-2018
- Nigel Tapper (Monash University, Australia): 2014-2018
- Aya Hagishima (Kyushu University, Japan): 2015-2019

* *appointed members*

IAUC Committee Chairs

Editor, IAUC Newsletter: David Pearlmutter
Bibliography Committee: Matthias Demuzere
Nominating Committee: Tim Oke
Chair Teaching Resources: Gerald Mills
Interim-Chair Awards Committee: Jennifer Salmond
WebMaster: James Voogt

Newsletter Contributions

The next edition of ***Urban Climate News*** will appear in late March. Items to be considered for the upcoming issue should be received by **February 29, 2016** and may be sent to Editor David Pearlmutter (davidp@bgu.ac.il) or to the relevant section editor:

News: Paul Alexander (paul.alexander@nuim.ie)

Conferences: Jamie Voogt (javoogt@uwo.ca)

Bibliography: Matthias Demuzere (matthias.demuzere@ees.kuleuven.be)

Projects: Sue Grimmond (Sue.Grimmond@kcl.ac.uk)

Submissions should be concise and accessible to a wide audience. The articles in this Newsletter are unrefereed, and their appearance does not constitute formal publication; they should not be used or cited otherwise.