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Review

Sensors and the city: a review of urban meteorological networks

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ABSTRACT: The heterogeneous nature of urban environments means that atmospheric research ideally requires a dense network of sensors to adequately resolve the local climate. With recent advances in sensor technology, a number of urban meteorological networks now exist with a range of research or operational objectives. This article reviews and assesses the current status of urban meteorological networks, by examining the fundamental scientific and logistical issues related to these networks. The article concludes by making recommendations for future deployments based on the challenges encountered by existing networks, including the need for better reporting and documentation of network characteristics, standardized approaches and guidelines, along with the need to overcome financial barriers via collaborative relationships in order to establish the long-term urban networks essential for advancing urban climate research.

KEY WORDS urban sites; meteorological stations; wireless sensor networks; meso-scale; city scale; micro-scale; cyber-infrastructure

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1. Introduction

Networks of meteorological sensors are essential to monitor atmospheric processes, and to assess both long-term climate change and short-term weather events. The importance of networks for monitoring climate is recognized by the IPCC (2001), who note that *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. Traditionally, national or global networks have not instrumented urban areas, as these networks are designed to collect standardized, representative climatological measurements of the wider region for subsequent use in weather prediction models and long-term climate. However, from the early work to understand regional climates (Howard, 1818) there has been increasing interest in the field of urban meteorology, climatology and air quality, which have since developed into sub-disciplines in their own right. Urban environments are becoming increasingly important and relevant to study since more of the world's population now inhabit towns and cities (UN, 2009; Grimmond *et al*., 2010), and as such, the proportion of the world's land and water surface covered by built-up environments is constantly expanding. It is therefore essential to better understand atmospheric processes and impacts in urban areas and how they will be affected by climate change.

Traditional meteorological monitoring stations in cities are both difficult and costly to deploy and maintain, ultimately resulting in sparse data coverage. Urban areas are complex and morphologically heterogeneous environments (Stewart and Oke, 2009). The spatial and temporal variability of climate across whole cities or regions cannot be represented by individual monitoring stations and indeed, the precise siting of any equipment is difficult (see WMO, 2006, for a guide to positioning of meteorological equipment in urban areas). Consequently, measurements from just a few of these meteorological monitoring stations do not provide the sufficient detail for urban climate research and decision-making applications (WMO, 2008). Thus, the only appropriate way to monitor such environments is with dense sensor networks. Such networks maximize understanding of the urban environment, as well as any changes that are occurring and likely impacts. Remote sensing techniques often provide a means for interpolation (Tomlinson *et al*., 2012), but are limited in the sense that they do not allow appropriate spatial or temporal resolution or a wide enough range of variables to be observed.

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With recent advances in technology, communications, miniaturization of electronics and computing power, environmental sensors are becoming more innovative, reliable, compact and inexpensive (Grimmond, 2006; Rundel *et al*., 2009). Thus for the equivalent prior purchase costs it is now possible to obtain more sensors of than previously without overly compromising quality of measurements. This provides an increased potential for urban networks of meteorological sensors which may be more numerous and densely spaced, with vastly improved temporal collection and rapid data transmission.

Depending on the application, networks of different sizes are required to study the range of atmospheric processes, at various spatial and temporal scales (Table I). Where observations from national networks inform global and regional models, finer-density observational networks are required for more detailed resolution of smaller scale processes. For example, within urban environments, atmospheric processes occur at the micro-scale to meso-scale (e.g. such as evaporation, convection, precipitation, wind, heat, radiation, surface fluxes, pollution development, dispersion, deposition). Hence, a new generation of atmospheric observation networks will permit new insight into urban atmospheric processes. The aim of this article is to provide guidance and a first 'point-of-reference' for implementing urban meteorological networks. This is achieved by reviewing the current status of urban sensor networks [with a focus on networks within the Urban Canopy Layer (UCL)] along with scientific and technical concepts of sensor networks, identifying current challenges, proposing recommendations for the future.

2. Characterization of Urban Meteorological Networks

By definition, a network does not necessarily have to be permanent and indeed they are often dynamic as technology, funding and objectives change. Short-term field campaigns are more common, set-up on a temporary basis to collect data over a short period of weeks, months or occasionally years (see Grimmond, 2006 for a detailed overview of these studies). As such, it is sometimes difficult to make the exact distinction between a campaign and a permanent network. Indeed, many campaigns may be set-up with the intention of becoming permanent, but have been discontinued due to funding difficulties. Consequently, this review focuses on urban meteorological sensor networks with near-real time communication capabilities which have the potential to become semi-permanent installations. A number of these have been implemented in several cities across the world in recent years and are summarized in Table II. The specific objectives of a network dictate the appropriate scale of atmospheric processes to be observed. This, along with resource availability, impacts the physical arrangement of sensors, communication systems, power sources, and the topology and size of the network (for a complete overview of sensor networks see Dargie and Poellabauer, 2010). There are also a number of additional logistical and scientific issues that need to be addressed when considering sensor networks and here we address those that are of particular relevance to urban meteorological networks.

2.1. Size and scale

Each network contains an organized collection of individual sensors which gather measurements that are either representative of the micro-climate (micro-scale), local climate (neighbourhood/local-scale) or regional climate (meso-scale – a single station is not able to represent this scale over urban areas; Oke, 2004) depending on the network objectives. The atmospheric processes that are to be observed, and the size and morphology of the area being covered, will impact on the physical arrangement of the network – such as the distance between the sensors, the sensor heights, and the precise location of the sensor – and thus the network scale.

Meso-scale networks observe regional atmospheric processes and weather phenomenon such as thunderstorms and squall lines – such processes are often hazardous, but cannot be adequately captured by individual monitoring stations, particularly over urban environments (Oke, 2004). Meso-scale networks potentially extend over hundreds to hundreds of thousands of square kilometres, covering both urbanized, peri-urban and rural areas. For example, a number of regions around the world have operational meso-scale networks ('mesonets') which aid the nowcasting of severe weather events and therefore prove very popular amongst a range of end-users (see Table II for a comprehensive list of metropolitan mesonets). As evident in Table II, these are particularly common in the United States – for example, UrbaNet is a US national network comprising of several metropolitan mesonets, which aims to explore the use of integrating commercial and government meteorological data over urban environments (NOAA, 2007). The Oklahoma Mesonet is one of the best documented examples in the literature (Crawford and Long, 1993; Brock *et al*., 1995; Fiebrich *et al*., 2003; McPherson *et al*., 2007; Fiebrich *et al*., 2010). The network was set up in 1987 and has served as the foundation for meso-scale monitoring of surface-layer processes (Fiebrich *et al*., 2003). The Oklahoma Mesonet now consists of more than 120 meteorological stations, evenly spaced across the state (18 000 km^2). A further (non-US) example is the Helsinki Testbed, which is a large scale measurement facility consisting of nearly 300 sensors, originally set up by Vaisala Oyj and the Finnish Meteorological Institute (FMI). The meso-scale network covers an area of Southern Finland (150 km^2, Poutiainen *et al*., 2006) including the city of Helsinki, rural and peri-urban areas.

City-scale networks focus on urban climate and atmospheric processes by using networks of instruments that allow sufficient coverage. Whilst an urban area could be considered a meso-scale phenomenon, meso-scale networks are not specifically designed to resolve the urban

Table I. Relations between spatial scales and climate networks, from largest to smallest areal extent.

Spatial scale areal extent	Description	Atmospheric processes and applications	Network examples
Global $> 10^8$ m	Global network of networks, internationally facilitated	Synoptic forecasting, global climate change, modelling, satellite calibration/validation	Global surface temperature monitoring networks, i.e. NOAA Global Historical Climate Network (GHCN); Global Climate Observing System (GCOS)
Macro-scale/Synoptic 10^5-10^7 m	Networks of national meteorological monitoring stations located around countries, usually in rural areas. Used for examining regional and national synoptic events	National weather forecasting (extratropical cyclones, baroclinic troughs and ridges, frontal zones), modelling	US Automated Weather Observing System (AWOS), US Climate Reference Network (USCRN), AMeDAS, Japan, and the UK Met Office MIDAS network have stations in rural and urban areas that provide hourly surface weather data for weather forecasting, aviation. These data are also provided to global data networks
Regional/Meso-scale[a] 10^4-10^6 m	Monitor regional meso-scale weather events. Urban, peri-urban and rural areas covered. Meso-scale meteorological events are often hazardous and might go undetected without densely spaced weather observations. Individual monitoring equipment representative of the local or micro-scale climate – meso-scale measurements from individual sensors not possible over urban environments (Oke, 2004)	Thunderstorms, downbursts, squall lines, temperature variations over urban and rural areas, sea circulations	Coarse array networks – currently several Mesonets ('meso-scale networks') e.g. in the US, China, Finland
City-scale[a] ,[b] 10^4-10^5 m	Monitoring weather and climate at the scale of the whole city. Individual monitoring equipment representative of the local or micro-scale climate – city-scale measurements from individual sensors not possible over urban environments (Oke, 2004)	Urban heat island studies, urban climate studies, air pollution	Fine-array networks such as the Oklahoma City Micronet, installed to examine urban climate variability
Local-scale/Neighbourhood[a] 10^2-10^4 m	Effects of minor landscape features (parks, ponds, small topographic features) neighbourhoods with similar types of urban development (surface cover, size and spacing of buildings, activity). Monitoring equipment is sited to be representative of neighbourhood (i.e. a set height, representative surface cover, little obstructions, to avoid micro-climate effects)	Urban heat island, variations with land use, surface cover, air pollution, tornadoes	Few local-scale networks exists, since most individual climate stations within city-scale networks or meso-scale networks are often representative of the neighbourhood in which it is located (unless they are specifically examining micro-climates). Urban networks are usually city- or meso-scale since dense networks are not necessary to assess local-scale climate over similar land use types
Micro-scale[a] $\leq 10^2$ m	Micrometeorological phenomena. Influenced by urban areas the dimensions of component elements: buildings, trees, roads, streets, courtyards, and gardens. Equipment located to be representative of the micro-climate	Urban canyon studies, turbulence and dispersion studies, human comfort and exposure, impact of buildings, agricultural meteorology	Some micro-scale networks such as uScan project, Tokyo, have been used to examine fine-scale temperature variations over complex infrastructure

[a]Scales which are important in urban studies.
[b]Scale added for the purpose of defining urban networks, since many networks are smaller than meso-scale networks but larger than local-scale networks, covering just the urban areas – spatial scale wide-ranging as depends on size of city.

Table II. Examples of urban climatological monitoring networks organized by horizontal scale or areal extent of the network.

Scale[a]	Network/Site/ Project name	City/Area	Approximate spatial extent	Number of sites	Time period	Measurement variables	Main aims of project/network	Communication method	References/ websites
Meso-scale	The Helsinki Testbed [FC to QN]	Helsinki, Finland	150 km^2	102 approximately	2005 to present	T, P, RH, DIR, SPD, PRECIP	Open research and quasi-operational programme designed to advance understanding of meso-scale meteorology	Cell-phone base stations masts	Dabberdt *et al*., 2005; Poutiainen *et al*., 2006; Koskinen *et al*., 2011; http://testbed.fmi.fi/
	Oklahoma Mesonet[b] [PN]	Oklahoma	181 000 km^2	120 (at least 1 in each 77 counties)	1994 to present	RAD_SW, P, PRECIP, DIR and SPD (10 m), T and R (1.5 m) SOIL_TEMP (10 cm depth); TSURF – measured at 89 sites in 1999	Multipurpose operational network providing research-quality data	Radio	Crawford and Long, 1993; Brock *et al*., 1995; Fiebrich *et al*., 2003; McPherson *et al*., 2007; Fiebrich *et al*., 2010; http://www.mesonet.org/
	Kentucky Mesonet[b] [PN]	Kentucky, USA	105 000 km^2	58	2010 to present	PRECIP, T (1.5 m), RH RAD_SW, SPD and DIR (10 m)	Research grade network of automated weather and climate monitoring stations	Commercial cellular communication	Grogan 2010; http://www.kymesonet.org/
	West Texas Mesonet[b] [PN]	Lubbock, Texas, USA	Within 250 km^2 of Lubbock	40 automated weather stations (plus 2 atmospheric profilers, 1 upper air sounding)	1999 to present	SPD (scalar and vector, 10 m), DIR (10 m), SPD (2 m), T (1.5 m, 9 m), P, PRECIP, RH (1.5 m) TD, RAD_SW, SOIL_TEMP (5 cm, 10 cm, 20 cm), SWC (5 cm, 20 cm, 60 cm, 75 cm), LEAF_WET	To provide free, timely, accurate meteorological and agricultural data	Extended Line of Site Radio System (ELOS), later cellular telephone for some sites	Schroeder *et al*., 2005; http://www.mesonet.ttu.edu/

Table II. (*Continued*).

Scale[a]	Network/Site/ Project name	City/Area	Approximate spatial extent	Number of sites	Time period	Measurement variables	Main aims of project/network	Communication method	References/ websites
	NYC Mesonet[b] [PN]	New York City, USA	NS	Various networks (inc. 30 CCNY; 4 airport)	2003 to present	Various	Assimilation of existing meteorological stations to provide real-time high resolution coverage for scientific and real-time requirements of the urban atmospheric observatory NYC	NS	Reynolds, 2003
	Alabama (/Tennessee) Mesonet (ALMNet)[b] [PN]	Alabama, USA	7900 km^2	24 (21 in Alabama; 3 in Tennessee)	2002 (/2003) to present	PRECIP, T, RH, RAD_UV, SPD, DIR, SWC, SOIL_TEMP	Part of Soil Moisture Experiment (SMEX '03), weather forecasting, research	NS	Coleman, 2005; http://wx.aamu.edu/ALMNet.php
	University of South Alabama Mesonet (USA Mesonet)[b] [PN]	South Alabama, USA	Spans 13 Gulf Coast counties across 3 states	26	2005 to present	18 variables	Weather Forecasting, severe weather warnings, research, education, public, agriculture, climate, water resource management	NS	Kimball and Mulekar, 2010; http://chiliweb.southalabama.edu/
	Iowa Environmental Mesonet[b] [PN]	Iowa, USA	NS	Approximately 500 (owned by different networks)	2001 to present	T, RH, SPD, DIR, P, PRECIP	Coordinates the collection, archival, and dissemination of environmental data from numerous existing sources	NS	Todey *et al*., 2002; http://mesonet.agron.iastate.edu/

Table II. (*Continued*).

Scale[a]	Network/Site/ Project name	City/Area	Approximate spatial extent	Number of sites	Time period	Measurement variables	Main aims of project/network	Communication method	References/ websites
	Georgia Automated Environmental Monitoring Network (GAEMN)[b] [Off]	Georgia, USA	NS	81	1991 to 2011	T, RH, PRECIP, RAD_UV, SPD, DIR, SOIL_TEMP (2, 4, 8 in.), P, SWC	Weather and environmental research variables for agriculture, environmental research and other applications	NS	Hoogenboom, 1993; http://www.griffin.uga.edu/aemn/cgi-bin/AEMN.pl?site=GAEB
	Arizona Meteorological Network (AZMET)[b] [PN]	Arizona, USA	NS	28	1986 to present	T, RH, SOIL_TEMP, RAD_UV, PRECIP, SPD, DIR	To provide full meteorological data and weather-based information for agricultural and horticultural purposes	NS	Russell, 2004; http://ag.arizona.edu/azmet/
	North Carolina ECONet[b] [PN]	North Carolina, USA	NS	36 (at least one in every county)	2001 to present	Various	To provide data to government agencies for improving emergency management, weather forecasts, energy planning, and natural resource management	NS	Fall, 2003; http://www.nc-climate.ncsu.edu/econet
	Open air Laboratories (OPAL)/London grid for Learning [PN]	Mostly London, UK (other UK urban areas now included)	1577 km^2 (Greater London)	91 (36 across London, 55 in other urban areas across the UK)	2009 to present	T, P, RRATE, DIR, RH, RAD_UV	Education	School WiFi	Davies *et al*., 2011; Ryder and Toumi, 2011; http://weather.lgfl.org.uk/
	London Air Quality Network (LAQN) [PN]	London, UK	1577 km^2 (30 Greater London Boroughs and Heathrow)	Approximately 130 in operation (~90 offline)	1992 to present	CO, CO_2, NO, NO_2, O_3, PM10, PM2.5, SO_2, C_6H_6, P, PRECIP, RH, RAD_SW, T, DIR, SPD	Air quality monitoring with meteorological variables collected at some sites	Broadband internet/telephone modem	http://www.londonair.org.uk/

Table II. (*Continued*).

Scale[a]	Network/Site/Project name	City/Area	Approximate spatial extent	Number of sites	Time period	Measurement variables	Main aims of project/network	Communication method	References/websites
	DCNet[b] [PN]	Washington DC, USA	177 km^2	16	2003 to present	T, RH, SPD, DIR, TI	Forecasting dispersion of hazardous trace gases and particles in urban areas	NS	Hicks *et al*., 2012
	Vancouver Island School-Based Weather Station Network	Vancouver Island, BC, Canada	2500–3000 km^2	138	2002 to present	T, RH, SPD, DIR, P, PRECIP, RAD_UV	Education	School broadband	Wiebe, personal communication; Wiebe, 2012; http://www.islandweather.ca/
City-scale	Oklahoma City Micronet (OKCNET) [Off]	Oklahoma, USA	1440 km^2	40 (36 micronet; 4 mesonet)	2007–2010	T, P, PRECIP, RH, SPD, DIR	Operational surface observing network designed to improve atmospheric monitoring across the Oklahoma City	Public OKC LAN	Basara *et al*., 2010; http://okc.mesonet.org
	Metropolitan Environmental Temperature and Rainfall Observation System (METROS) [Off]	Tokyo, Japan	2187 km^2	120	2002–2005	T, RH, SPD, DIR, PRECIP, P	Temperature and precipitation observing system	NS	Mikami *et al*., 2003; Takahashi *et al*., 2009
	Taipei Weather Inquiry-Based Learning Network (TWIN) [PN]	Taipei, Taiwan	271.79 km^2	60	2003 to present	T, RH, P, RAD_SW, RRATE, DIR, SPD	Education/public information	School WiFi	Chang *et al*., 2010; http://www.aclass.com.tw/products.aspx?BookNo=weather_01

Table II. (*Continued*).

Scale[a]	Network/Site/ Project name	City/Area	Approximate spatial extent	Number of sites	Time period	Measurement variables	Main aims of project/network	Communication method	References/ websites
	Community Weather Information Network (Co-WIN) [PN]	Hong Kong	1104 km^2	105	2007 to present	T, RH, PRECIP, SPD, DIR, P, UVA/B, RAD_SW	Encourage community participation, promote weather and climate education and raise awareness of environmental issues, such as climate change, acid rain and urban heat island	School and other institute's wireless or LAN	Hung and Wo, 2012; http://weather.ap.polyu.edu.hk/
	Berlin City Measurement Network [PN]	Berlin, Germany	891.82 km^2	10	2000 to present	Various measurements at each site, inc.: T (5 cm, 2 m, 6 m, 12 m), RH, PRECIP, SOIL_TEMP, DIR, SPD, P	Operational/research	Datalogger plus a range of telephone, internet, Ethernet cable	Müller, personal communication; http://www.geo.fu-berlin.de/en/met/service/stadt-messnetz/index.html
	Quantum Weather [PN]	St. Louise, Missouri, USA	NS – currently city-scale (meso-scale network planned)	50 (100 planned)	2008 to present	T, P, SPD, DIR, PRECIP, RH	To provide dedicated real-time forecasts of weather hazards at the neighbourhood level impacting the AmerenUE electric power grid in eastern Missouri	Wireless	Mueller *et al*., 2009; http://www.ameren.com/sites/aue/source/Outage/Pages/QuantumWeather.aspx

Table II. (*Continued*).

Scale[a]	Network/Site/ Project name	City/Area	Approximate spatial extent	Number of sites	Time period	Measurement variables	Main aims of project/network	Communication method	References/ websites
	CitySense [Off]	Cambridge, MA, USA	18.47 km^2 (Local-scale achieved to-date)	25 (100 proposed)	2006–2010	T, P, PRECIP, RH, SPD, DIR, CO_2, NOISE	City-wide wireless network testbed for monitoring weather conditions, air and water pollution, biochemical agent concentration located on lampposts and buildings	Dual WiFi 802.11a/b/g radios (multi-hop urban mesh network)	Murty *et al*., 2008; Matt Welsh, personal communication; Welsh and Bers, 2010; http://www.citysense.net/
Micro-scale	UScan [FC]	Tokyo, Japan	8 sites in 250 m by 430 m	200	July–Aug 2007	T, VIB, ILLUM	To examine fine-scale temperature variations over complex infrastructure and to examine the impacts of street widths, orientation, trees	Wireless mesh	Ono *et al*., 2008; Thepvilojanapong *et al*., 2010
	Lausanne Urban Canopy Experiment (LUCE) [FC]	École Polytechnique Fédérale de Lausanne (EPFL) university campus, Lausanne, Switzerland	750 m by 500 m	92	October 2006 to April 2007	TSURF, T, P, RH, SPD, DIR,	To estimate the sensible heat flux over the built environment under convective conditions	Wireless	Nadeau *et al*., 2009; http://eflum.epfl.ch/research/landatm/urban
	Sensor Network over Princeton (SNOP)	Princeton University, Princeton, USA	Approximately 300 m by 300 m	7	NS	T, RH, SWC, SOIL_TEMP, RAD_LW, RAD_SW, TSURF, SPD, DIR	Urban micrometeorology research	Wireless	http://efm.princeton.edu/Sensor_Networks.htm; http://efm.princeton.edu/SNOP

Table III. (*Continued*).

Scale[a]	Network/Site/ Project name	City/Area	Approximate spatial extent	Number of sites	Time period	Measurement variables	Main aims of project/network	Communication method	References/ websites
	Woodlawn High School Network (WHSN)	Baltimore, USA	Approximately. 400 m by 400 m	7	NS	T, RH, SWC, SOIL_TEMP, RAD_LW, RAD_SW, TSURF, SPD, DIR	Urban micrometeorology research	Wireless	http://efm.princeton.edu/BalNet

Earth relative wind direction (DIR); Earth relative wind speed (SPD); Station pressure (P); Air temperature (T); Dew point temperature (TD); Relative humidity (RH); Precipitation (PRECIP); Rain rate (RRATE); Surface temperature (TSURF); Turbulence intensity (TI); Long wave radiation (RAD_LW); Shortwave radiation (RAD_SW); UVA (UVA); UVB (UVB); Soil temperature (SOIL_TEMP); Leaf wetness (LEAF_WET); Noise (NOISE); Vibration (VIB); Illumination (ILLUM); Carbon dioxide (CO_2); Nitrogen Dioxide (NO_2); Sulphur Dioxide (SO_2); Ozone (O_3); Carbon Monoxide (CO); Particulate Matter <10 µm (PM10); Particulate Matter <2.5 µm (PM2.5).

[PN], (semi)permanent network; [QN], quasi-operational network; [FC], field campaign; [Off], network offline, but still collecting data; NS, no information supplied.

[a] Areal extent of the network (not representativeness of individual measurements).

[b] A number of mesonet sites in the US have ceased operation, are currently operating or are being set up, therefore this list may be incomplete. 'UrbaNet' (http://madis.noaa.gov/urbanet.html) comprises of a number of US metropolitan mesonets.

climate. Instead, dense climate networks covering whole cities are required to examine the urban climate in more detail (Table II). Such networks are used for monitoring and modelling phenomenon such as the Urban Heat Island (UHI), urban air quality and hazardous phenomena (i.e. tornadoes, thunderstorms and squall lines), which cannot be adequately captured by individual monitoring stations (Oke, 2004). The precise size and coverage of a city-scale network is dependent upon the spatial extent and morphology of the city being monitored. Individual measurements will be representative of either the neighbourhood the sensor is located in, or the micro-environment, depending upon where and how the equipment is sited. The Oklahoma City Micronet (OKCNET) is one example of such networks (Basara *et al*., 2010). OKCNET was set up in 2008 as an operational network at a finer scale than the Oklahoma Mesonet (where stations are typically located away from urbanized areas to maintain the site representativeness requirements of the network). It covers the main urban area of Oklahoma City (1440 km^2) and consists of 4 Mesonet sites and 36 Micronet stations mounted on traffic signals at heights of approximately 10 m, with an average spacing of 3 km (Basara *et al*., 2010). Measurements taken by each sensor are considered representative of the local area (and not the micro-climate). Metropolitan Environmental Temperature and Rainfall Observation System (METROS) is another such example, located across Central Tokyo (2187 km^2). The high spatial and temporal resolution supplement and measurement network was designed to complement the nationwide Automated Meteorological Data Acquisition System (AMeDAS) network and consisted of 120 climate stations, mostly deployed at schools (Mikami *et al*., 2003).

Micro-scale networks observe atmospheric processes over small areas, such as turbulence within street canyons, air pollution dispersion, micro-climate studies, and infrastructure impacts on local temperature. These small networks are only representative of the specific area in which the sensors are placed (i.e. the micro-climate). Observations can be used for developing and evaluating dynamical models, for human comfort and exposure assessments and to examine the impacts of buildings. Often, 'micro-scale' projects involving sensors do not constitute a 'network' *per se*, as the data stored by data loggers require manual download and are part of a short-term field campaign. However, there are some examples of interconnected micro-scale sensor networks (e.g. UScan, Ono *et al*., 2008; Lausanne Urban Canopy Experiment (LUCE), Nadeau *et al*., 2009; Table II), and with increasing use of wireless technology and miniaturization of devices, these are likely to increase.

The 'confusion of scales' has recently been highlighted as a common flaw in the investigation of urban climate (Stewart, 2011), and this notion is also applicable for urban meteorological networks. For classification of urban networks (Table I), there are a number of factors that need to be considered: the areal extent of the network (often reported as 'network scale') and therefore the environments covered; the spatial resolution of the network – the density of individual sites and distance between the sensors; and the spatial representativeness or scale length of the individual measurements, which is dependent on the actual location of the instrumentation, morphology of the area, measurement interval, exposure, and fetch (WMO, 2006). For example, a sensor network may be classified as a 'meso-scale network' since it covers an area of hundreds of square kilometres which consist of urban, peri-urban, and rural areas and can therefore observe meso-scale events. However, depending on certain factors – such as the topography of the area, where the sensors or monitoring stations have been located (i.e. at what height, over what land class type, at what distance from buildings, etc.), and the actual number of sensors deployed across the networks – the individual measurements and the resolution of the network could be very different (i.e. micro-climate *vs* local-climate *vs* regional-climate, dense array *vs* coarse array). Also, using 'areal extent' alone to classify a network is risky, since a meso-scale network in one country may indeed be a city-scale network in another (e.g. Helsinki Testbed, Poutiainen *et al*., 2006, *vs*. OKCNET, Basara *et al*., 2010). Given the likelihood of increasing numbers of these networks, there is a need for a clear distinction between these urban network descriptions. For example, it is necessary to standardize the specific terms used to define network scales and outline what details are necessary. This information would provide a clear indication of the atmospheric processes that are observed by each network, and therefore the potential additional applications of the network for research and operational purposes, and critical details for cross-network comparisons. Currently, much of this information is provided within the literature for some network, but is lacking for others (Table II).

2.2. Locations

Finding suitable sites and secure locations in urban areas can be difficult. WMO guidelines (2006, 2008) for siting meteorological equipment in urban areas need to be adhered to as closely as possible, in order to ensure the monitoring equipment is collecting representative data (which will depend upon the aim of the specific study or network). It is accepted that this is often logistically difficult in urban areas, but simple steps can still be taken to improve data quality (e.g. use of standardized measurement heights and unobstructed equipment and representative locations – see WMO (2006) for a detailed overview of urban site selection criteria for specific meteorological equipment). Ultimately, it is the need to locate instrumentation in a secure site away from the threat of vandalism without contravening WMO guidelines which poses the biggest challenge. All details including deviations from guidelines should be logged via thorough 'metadata' (additional information about the whole network), which is essential in order to provide a data end-user with the information required to process and adequately use the network's data (McGuirk and May, 2003). For example, Brock *et al*. (1995) provide an excellent example of how to report urban network metadata and technical information, whilst WMO (2008) provide guidance on metadata collection for urban stations.

Issues surrounding the aesthetics or 'visual appeal' of instruments in urban areas can also pose challenges. In some cases this may present a potential roadblock for progressing with network implementation and the deployment of instrumentation. Where possible it is advisable to get site owners, neighbours and/or associated personnel on-side beforehand or even approach them to become project partners during the networks planning stages by highlighting the purpose and co-benefits of the network. With evolving technologies miniaturization may in some cases make sensors less conspicuous.

Furthermore, there are legal issues to consider, such as licenses, risk-assessments, and agreements for siting equipment on private property to ensure that liabilities and responsibilities are clearly outlined. Examples in the literature include schools, colleges or universities [e.g. Open Air Laboratories (OPAL), Davies *et al*., 2011; Taipei Weather Inquiry-Based Learning Network (TWIN), Chang *et al*., 2010], lampposts or traffic lights (e.g. OKCNET, Basara *et al*., 2010), mobile-phone base-station masts (e.g. Helsinki, Koskinen *et al*., 2011) and security-patrolled sites. Due to ease of access and consistent site surroundings, schools are a popular location for siting monitoring equipment and as a result, a number of 'educational' urban climate networks have appeared around the world (Table II). The focus of such networks is often educational, but they do provide an example of how equipment can be installed in a relatively secure location and utilize existing communication networks. One example of an educational climate network forms part of the OPAL project, which is a community research programme focused on environmental themes (Davies *et al*., 2011). The OPAL London weather station network more than 36 weather stations have been installed on schools around London (at least one per London borough, Davies *et al*., 2011) making it one of the world's most extensive urban weather station networks.

2.3. Communication and internet accessibility

Communication is an essential component of any network. This consists of the data flow from the sensor to initial analysis, data management, data display, and usage (Figure 1), jointly termed the '*cyberinfrastructure*' (Hart and Martinez, 2006). This consists of computer systems, instrumentation, data acquisition, data storage systems and repositories, visualization systems, management services and technicians, linked by software and communication networks (Estrin *et al*., 2003; Brunt *et al*., 2007). The physical layout and the pathways of data flow between them are two characteristics of the network typology. These are both influenced by available technology, the spatial extent of the network and the time-sensitivity of the data. Several different types of network typologies exist including star, mesh, ring, line, tree and bus (Dargie and Poellabauer, 2010).

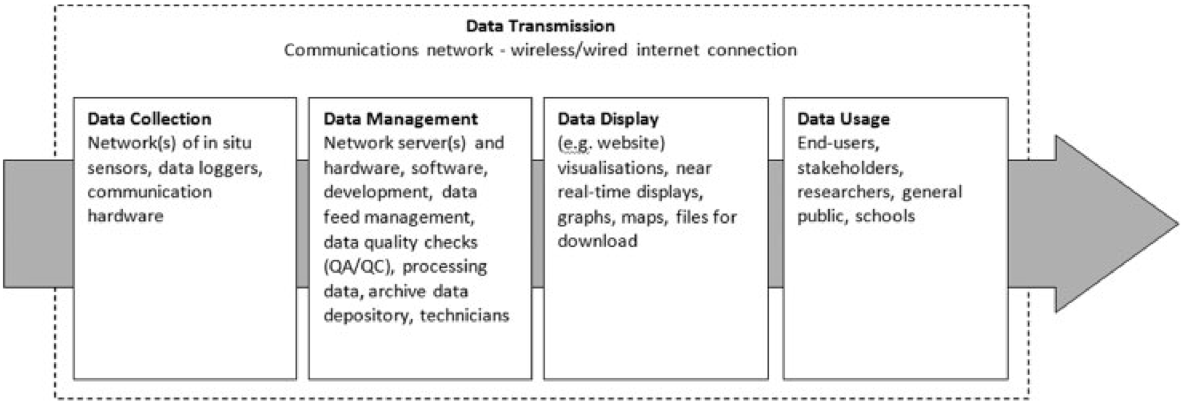

Figure 1. Schematic diagram of a communication system and network architecture for urban climatological monitoring ('cyberinfrastructure').

Traditionally, data loggers have been used in many environments to collect and store data. Such methods, however, do not allow for near-real time analysis or visualization if the data are not transferred. There are still many situations where communication networks are unavailable (i.e. due to coverage, signal strength, resources, etc.) or data does not need to be transmitted real-time, therefore the data can still be stored locally and collected manually at set intervals (Note, any system which requires manual collection is not technically classified as a network, but rather an organized collection of sensors). With technological improvements, there is a trend for such passive logging systems to evolve into active sensor networks of automated sensors and communication systems (Hart and Martinez, 2006). Nevertheless, most networks which transmit data automatically still utilize data loggers as a back-up for times when the data cannot be relayed over the network.

The majority of weather installations work on a 'star' network, relaying information back to the central host server over the internet via a wired Ethernet (IEEE 802.3 standard) connection (Dargie and Poellabauer, 2010). This can either be Local Area Network (LAN) or modem-based Digital Subscriber Line(DSL) /Asymmetric Digital Subscriber Line (ADSL) lines. This method is reliable and as a result is the preferred method for most sensor networks. However, this method requires the presence of network points which can often be impractical, obtrusive and costly (Hart and Martinez, 2006).

As a result, wireless transmission is a viable alternative option that is increasingly used for climatological sensor networks. Wireless sensor networks (WSN) consist of spatially distributed autonomous sensors whereby the data are passed wirelessly over the network to a main location (Akyildiz *et al*., 2002; Römer and Mattern, 2004). This can involve either utilizing Global System for Mobile communications (GSM)/General Packet Radio Service (GPRS) technologies, existing wireless networks, or setting up a bespoke WSN for the specific purpose of transmitting the data collected by the sensors. Other networks have used satellite, SMS text messaging, and radio communication systems to relay data back to a central base station. For example, the Oklahoma Mesonet uses the state-wide Oklahoma Law Enforcement Telecommunications System (OLETS) to transmit data back to central servers, since it provides reliability, bandwidth, and full two-way services (Crawford and Long, 1993; Brock *et al*., 1995). Urban areas are particularly well-placed to utilize wireless technology as there is a growing provision of numerous municipal wireless access points in urban areas, allowing almost complete coverage in most towns and cities. Hence, with the appropriate permissions these existing municipal wireless networks (open access or subscription wireless access points) can be utilized to relay data from sensors to the host server. These networks use the IEEE 802.11 Wireless LAN (WLAN) standard – often referred to as 'Wireless Fidelity' (WiFi) – which allows easy connection to conventional computers. Other WiFi networks in urban areas which could be utilized include school (e.g. OPAL utilizes individual school's broadband to transmit data to a central server) and public building networks which can be used to transmit data from equipment, if sited on school grounds, or other private networks (i.e. businesses, cafes, restaurants) covering the location of the sensor. Gaining access to the internet via existing wireless, GSM or radio infrastructures, such as school or public WiFi networks, can also be challenging. There may be security issues, access issues, and cost implications to resolve. It is also imperative the WSN communications are secure and encrypted to prevent computer hacking and data tampering at the software level. In addition, there are likely to be times when the network is unavailable, therefore the use of data-loggers to store data during these occasions is necessary so data can be transmitted once the network is back online.

Where finances permit, bespoke wireless communication networks using purpose-built base stations, or inter-node hoping to extend the range (i.e. mesh networks) can also be used as communication systems for WSN (Hart and Martinez, 2006). Essentially, sensor network nodes are a grid of wireless devices which are specifically set up to relay data across a network. Such WSN utilize the IEEE 802.15.4 standard which is a low-cost communication technology, created for low-power devices that operate in the 868, 915, and 2.45 MHz frequency bands (Gutierrez *et al*., 2001). 'ZigBee' is the commercial name for IEEE 802.15.4 technology (Dargie and Poellabauer, 2010) and is ideal for environmental applications (Polak and Hoose, 2009).

2.4. Energy requirements

The options available to power sensor networks depend on the location of the sensors, the specific power requirements and the nature of equipment involved. Where possible, and with the correct permissions, electricity from the main power grid can be utilized. This may involve utilizing the local electricity infrastructure, such as available on lampposts and traffic lights onto which sensors may be installed (e.g. OKCNET, Basara *et al*., 2010; CitySense, Welsh and Bers, 2010). However, when mains electricity is unavailable, batteries and/or renewable options such as solar and wind energy are a viable alternative. Solar panels are becoming more efficient and capable of powering new-generations of climate monitoring equipment. However, this has implications with respect to the choice of sensors available (i.e. low power requirements) and will limit the nature of equipment in the network. When using these alternative methods, it is essential that specific power requirements are accurately calculated. This includes the power required to run the sensor, transmit the data through the chosen communication methods (accounting for things such as measurement and transmission frequency), and to collect and store any data when the communication networks are unavailable.

2.5. Data collection and management

Calibration of equipment and instrument inter-comparison periods are essential to ensure the data quality. Sensor networks frequently contain low cost, non-standard, sensors and as such all equipment needs to be tested against a traceable 'standard' instrument. Ideally, equipment should be calibrated at a national standards/calibration lab. This ensures reliability of results and allows for comparison with other equipment calibrated to the same standard. Vast amounts of data are generated by dense sensor networks which may present a challenge to manage effectively (Rundel *et al*., 2009). Documented Quality Assurance and Quality Control (QA/QC) procedures must be used in order to provide end-users with high-quality data (Shafer *et al*., 2000; Fiebrich *et al*., 2010). These include details of any changes to the network or stations, methods for error-reporting, spatial and temporal coherency and internal consistency. For example, all the Oklahoma Mesonet equipment are calibrated using laboratory calibration facilities with literature providing details of the strict QA programme that is followed to maintain high data quality (Brock *et al*., 1995; Fiebrich *et al*., 2010). Other networks report similar procedures (e.g. Helsinki Testbed, Koskinen *et al*., 2011), yet this documentation is sometimes difficult to identify for other networks (e.g. TWIN, Chang *et al*., 2010; Quantum Weather, Mueller *et al*., 2009 – Table II) meaning it is therefore difficult to assess data quality. In some cases, the quality of the data is indeed questionable. For example, inter-comparisons were not carried out for instruments used in the OPAL network, whilst the manufacturer's calibration was used for the accuracy (Ryder and Toumi, 2011). Consideration also needs to be given as to where the data are initially stored and processed (including procedures for ensuring servers are secure and backed-up), archived long-term (in data repositories, e.g. British Atmospheric Data Centre, National Climatic Data Centre) and accessed by end-users.

2.6. Reporting, communication, and information dissemination

Oke (2006) identified a general need for better communication in urban climate literature. This includes technical reports (containing all the necessary information which are easily accessible) as well as peer-reviewed articles. With the exception of the United States (i.e. Brock *et al*., 1995) there appears to be a paucity of technical information in the literature related to urban sensor networks. In some cases, technical information about networks is difficult to locate, often very basic and relatively un-standardized in terms of the content or definitions used. For example, there is no accessible information regarding the installation and management of the OPAL network (Davies *et al*., 2011) e.g. technical information, metadata or QC criteria, therefore it is difficult to determine the quality of the network data for use in scientific research. This does not necessarily mean that procedures are not in place – despite being education-focused, the OPAL data have been used for academic research (Ryder and Toumi, 2011), thus at least some management procedures are expected to be implemented – but these are not publicly reported. This is the case for the majority of the networks in Table II.

Communication via informal methods, such as websites, is important for providing information to a variety of stakeholders. Many urban sensor networks have websites whereby data can be visualized and downloaded on requested (e.g. London Air Quality Network). For example, the Oklahoma Mesonet (Fiebrich *et al*., 2003) shares data with the research community as well as federal, state and local government users, schools and private agencies (in some cases a fee is charged to external research groups). Their website, outreach programme and decision-support system provide excellent examples of data dissemination and multipurpose uses (McPherson *et al*., 2007). The Helsinki Testbed (Koskinen *et al*., 2011) incorporates end-user product development and demonstrations, and data distribution for both the public and research communities. The public website has been particularly popular, with more than 950 000 unique visitors, particularly during extreme weather events (Poutiainen *et al*., 2006). Furthermore, a live data-feed is also shown on advertising screens on public transport. The OPAL project also disseminates data, near real time and are archived via the London Grid for Learning website (Davies *et al*., 2011).

2.7. Sustainability

Despite the World Climate Conference 3 and National Research Council identifying the need for urban meteorological networks (Grimmond *et al*., 2010; NRC, 2010), there is considerable difficulty in obtaining funding to maintain an already established network in order to produce the long-term urban climatological datasets required by science. For example, at the time of writing, although OKCNET (Basara *et al*., 2010) is still logging data (using automatic QA procedures), it is currently not fully operational due to financial constraints (Basara, 2011, personal communication). This is a recurrent issue when setting up small-scale sensor networks which are funded for a set period of time (e.g. METROS, Takahashi *et al*., 2009). Therefore, collaboration with other universities (national and international), interdisciplinary research groups, public or private companies, may allow for the continuation of already-established networks. For example, since installation of the Helskinki Testbed, over 15 multidisciplinary and collaborative research projects have utilized the data (see Koskinen *et al*., 2011 for details). This is one example of how a short-term research project which involved setting up a network of sensors, can evolve and attract the interest of a variety of end-users as a quasi-operational weather observation and measurement network and it provides an excellent demonstration of the potential for exploiting such small-scale networks.

Furthermore, one of the most problematic aspects of setting up a new network is contacts – finding suitable locations, the relevant people, and the appropriate network infrastructure. If this has already been achieved for an established network, the task of maintaining and/or expanding the network could utilize co-operative action. This could involve industrial stakeholders and other users providing piecemeal funding in order to sustain the network over the longer term – an extremely challenging aspect, particularly during a period of austerity. Hence, communication, knowledge transfer, public engagement, and educational outreach provide vital components in sustaining a network.

3. Conclusions

Complex, morphologically heterogeneous urban environments can now be studied at the fine detail necessary to obtain a better understanding of weather and climate interactions and impacts in these areas. However, robust planning, design, field documentation, installation, management, QA, and maintenance are essential parts of any successful network of sensors (Hart and Martinez, 2006). This review of a number of urban meteorological networks around the world has highlighted issues that need to be addressed when establishing and maintaining such a network. It is hypothesized that as a consequence of insufficient reporting, inadequate written documentation, or lack of promotion of a network, many key details are not available for a number of networks. It is likely many other urban networks have been unintentionally omitted from this review.

This review focused on networks within the UCL, but networks monitoring the boundary-layer are also necessary (Grimmond *et al*. 2010). Ideally, these will be combined with UCL networks to explore the vertical structure of the atmosphere above cities (from surface-layer to boundary layer monitoring). For example, sensors could be located vertically up tall buildings or masts within urban areas in order assess variations from surface-level through the boundary layer. However, Chen *et al*. (2012) note that this is likely to be challenging. Remote sensing instrumentation will be increasingly incorporated into urban networks (e.g. the Oklahoma Mesonet has infrared temperature sensors at 89 of its sites for monitoring skin temperature; Fiebrich *et al*., 2003) using a range of technologies such as radar, lidars, motes, fibre optic temperature measurements, and vertically pointing Micro Rain Radars (Muller *et al*., 2010). Some technologies will need further developments to be deployable in cities (e.g. sodars because of noise). In addition, it is likely that other platforms (e.g. unmanned aerial vehicles), new data sources (e.g. data from sensors in buildings, mobile-phones, and cars), and better communication technologies (e.g. 4 G and beyond) will become available for use in urban networks (Chen *et al*., 2012).

However, given the vulnerability of cities to numerous meteorologically related events, there is currently a paucity of high quality urban meteorological networks in existence. The key barriers to deployment are a lack of financial backing accompanied by the constraints of placing expensive equipment in urban areas (e.g. vandalism, siting, permissions). As others have already noted (Grimmond *et al*., 2010; NRC, 2010), more long-term, high-density urban climate networks are required in order to improve understanding of this important environment. However, it is essential that best practice and results are shared within the sensor network and urban climatology communities. A successful network will need collaborative relationships with academic and government institutions and commercial companies. All technical information, thorough metadata, datasets, results and lessons learnt need to be published in order to be able to cross-reference networks and build on experiences. To this end, there is a clear need for stronger guidelines and more standardized approaches for urban meteorological networks in order to advance this field. For example, documents for aiding network design (Stewart and Oke, 2012) and standardized metadata practises.

More importantly, a long-term view of network implementation is required. This is essential in order to produce the baseline datasets needed for urban climatology applications and research. A concerted effort is needed to prevent established networks from being taken offline or decommissioned, as appears to be the fate of many networks. The benefit and value of such networks needs to be communicated to a variety of end-users in order to secure continued funding sources (Koskinen *et al*., 2011). In cases where networks are decommissioned, recycling or re-using equipment, resources, network infrastructure, knowledge and expertise with other sensor networks and projects should be examined as one possibility for making the most of resources and encouraging collaboration. Overall, the future use of urban sensor networks for urban meteorological monitoring and research is encouraging, but requires a coordinated approach to highlight technical issues, share best practice, experiences, recommendations and datasets, and to standardize approaches, where possible, in order to progress the field of urban meteorological research.

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