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Micro- and mesoclimatology

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Abstract: This report focuses on research in this area published during 2007. It reflects the broad themes that emerged in the literature during this period, with an emphasis on urban-based work. Urban-based climatology is assuming increased importance in the literature for a number of reasons, including the inherent complexity of urban environments, which makes their study difficult, and the potential for purposeful use of micrometeorology to improve the environment experienced by most of the population. Moreover, 2007 provided a rich vein of work in this area. The report is divided into two main sections, associated with the surface energy budget and its application to 'natural' settings and the study of urban climates.

Key words: energy budget, heterogeneous landscapes, urban climates.

I Surface energy budget and its application to 'natural' settings

The basis for understanding the behaviour of climates close to the ground is provided by the surface energy balance, which (for a simple surface) states that net radiation (Q^*) is partitioned into turbulent sensible (Q_H) and latent (Q_E) heat fluxes and transfer of sensible heat into the substrate via conduction (Q_G):

$$Q^* = Q_H + Q_E + Q_G$$

The Q^* term may be decomposed into incoming short ($K\downarrow$) and long-wave ($L\downarrow$), reflected short-wave ($K\uparrow$) and emitted long-wave ($L\uparrow$) radiation terms. Conventionally, each of these terms is assessed for a vertical distance above an active 'surface' where exchanges are at a maximum. For vegetated surfaces, the active surface is displaced from the ground itself by the aggregate effects of the individual vegetation elements, which make up a canopy. The nature of this displacement is governed by the architecture of the canopy. Thus, a closed canopy will effectively provide a 'surface' for the overlying boundary layer, while the layer below experiences a distinctive canopy layer climate.

In ideal circumstances, where the canopy forms a consistent and extensive surface cover, the fluxes at this 'surface' can be assessed by instruments located above it. In the case of radiation measurements, the view of downward-looking instruments (their 'footprint') is occupied primarily by the surface directly below, the area of which is constant and depends upon the distance separating the surface and the instrument level. On the other hand, the turbulent flux instruments record the passage of rapidly

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moving air parcels that move across their sensing elements and obtain wind velocity, temperature and water vapour concentrations. Most often, these fluxes are obtained through the eddy-covariance method whereby highly sensitive devices record the joint fluctuations in temperature and wind velocity, for example, to acquire Q_H. These instruments interrogate a random sample of the air parcels in motion close to the surface that have had different trajectories. As a result, the footprints of these instruments constantly change in area and shape. To ensure that all the flux observations are compatible, an extensive, homogenous surface is ideal so that the different 'footprints' associated with the instruments encompasses the same surface cover. In this manner, all the parcels passing across the instruments bear the imprint of the same underlying surface. In these circumstances, the horizontal exchanges are insignificant and vertical exchanges dominate. The substrate heat flux is obtained most often from a heat flux plate located below the ground surface. Ideally, precise measurement of these terms under ideal circumstances will 'close' the energy budget.

Where a landscape is heterogeneous in nature, obtaining a representative sample is difficult as observations will capture the varying contributions of the different surface types. To provide a coherent picture of the underlying exchanges requires a relatively complex assessment of the contributions of the distinctive surfaces to the overall flux observed. These contributions will change based upon the trajectory of the airflow and the stability of the atmosphere. Closing the energy budget in these circumstances is considerably more difficult.

There are a great number of individual energy budget studies reported in the literature but no general themes have emerged. As an example, Watts *et al.* (2007) report on the North American Monsoon Experiment conducted in 2004 and the concurrent changes in vegetation and surface energy fluxes that accompany the onset of the monsoon and the arrival of precipitation. Seven stations, located in different biomes, were located in Senora, Mexico, and Arizona to characterize this transformation. Not surprisingly, the response of subtropical forests was substantially different from arid environments. Q* was lower for the former and rates of Q_E higher; however, expected changes in surface albedo were not observed. The results are to be used to improve our understanding of monsoon dynamics and the role of land-atmosphere feedbacks. Elsewhere, Wendt *et al.* (2007) compare observations made over burnt and unburnt tropical savannah near Darwin, Australia. The fire scorched the above-ground vegetative canopy, reduced Q_E to near zero, and there were corresponding increases in Q_H and Q_G. As a result, the air above the burnt site was up to 2°C warmer than that over the unburnt site. The authors suggest that at a landscape scale such changes could form or alter mesoscale circulations that would later regional heating and cooling patterns.

A series of articles reporting on the Energy Balance Experiment (EBEX-2000) is extraordinarily illuminating (Oncley *et al.*, 2007; Mauder *et al.*, 2007; Kohsiek *et al.*, 2007). In essence, a very detailed field experiment was carried out to identify the reasons for the commonly observed inability to close the energy budget as outlined above (Oncley *et al.*, 2007). The site selected was a flat, irrigated cotton field 1.3 km^2 in area in the San Joaquin Valley, California, in 2000. During the experiment, skies were clear and the majority of Q* was expended on evapotranspiration. Observations were made at 10 sites at a height of 4.7 m and the footprint of each was contained entirely within the field. The authors considered errors arising from instrument calibration, instrument placement and data processing. Despite the great care taken in ensuring the veracity of the observations, the energy budget calculated for the field had an imbalance in the middle of the day of 70 Wm^{-2},

approximately 10% of the value of Q*. This 'error' was attributed to either the measurement of individual terms (especially Q_E), spatial variations in the site or the failure to measure other terms. Among the extraneous terms examined were vertical divergence between the top of the canopy and the level of measurement, advection and the energy consumed in the process of photosynthesis. While some terms could be neglected, the researchers were ultimately unable to offer an explanation for observed imbalance (on the order of 10%). That this was the case for such a carefully designed experiment provides a salutary lesson in the difficulties in obtaining good observational databases. The accompanying papers (Mauder *et al.*, 2007, and Kohsiek *et al.*, 2007) provide inter-instrument comparison of eddy-covariance and radiation sensors, respectively.

II The study of urban climates

In contrast to the energy balance equation presented above, the form of the equation employed in urban settings has the following form:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S$$

The substrate flux term has been replaced by a storage term to reflect the energy stored in the built fabric of the city and the substrate. In addition, an anthropogenic heat flux (Q_F) is included to account for the significant amount of energy released into the urban atmosphere by human activities. There have been many attempts to obtain values for Q_F employing both direct measurements and censuses of energy use. Pigeon *et al.* (2007a) obtained estimates using both approaches for Toulouse, France, that suggest values in dense, central city, areas during the winter Q_F can achieve values of ~100 Wm^{-2} while suburban values of between 5 and 25 Wm^{-2} are attained.

Research into the urban effect on climate remains a very important strand of physical geography. From my viewpoint, the geographer's perspective is distinguished by a concern for how a climatological understanding of process could be applied to urban planning and design. A good sense of the scope of the field, including its progress and gaps, can be obtained from a series of papers published in a special issue of the *International Journal of Climatology*. These papers represent a selection of those presented at the International Conference on Urban Climate, which was held in Göteborg, Sweden, in 2006 (Grimmond *et al.*, 2007). Among these is a review on the state of urban mesoscale modelling (Martilli, 2007) which highlighted the impact that increased computational power has had on the advancement of numerical models in this arena. Other papers examined the states of research into urban climates in arid (Pearlmutter *et al.*, 2007) and subtropical (Roth, 2007) regions. It is generally recognized that there is a need for a greater focus on the urban climates of the tropics, in particular, as this is where the majority of urban inhabitants on the planet currently reside. In the same vein, Emmanuel *et al.* (2007) assess the potential of an urban shading strategy to achieve comfort in Colombo, Sri Lanka.

Applying the energy budget to urban settings has proved problematic. In addition to their inherent spatial heterogeneity (a patchwork of different land covers, often small in size and proximate), they are comprised of substantial roughness elements (buildings) that pose real problems in positioning observing platforms. The lower part of the urban boundary layer (UBL), below the rooftops of buildings, is the urban canopy layer (UCL). In this layer, the outdoor air obtains its characteristics from the immediate environment (the walls of buildings and street surface) and properties advected from within the UCL or the overlying UBL. Just above the UCL is a zone where flow is dominated by the roughness elements and atmospheric properties change rapidly. Observations within this layer will have difficulty in assessing the source

contributions to the surface energy budget and consequently linking fluxes to underlying urban surface types. To achieve this, it is necessary to position instruments above this roughness sublayer at approximately twice the average height of buildings (Oke, 2006). It is important to recognize then that the placement of instruments within the urban environment has a significant impact on the results obtained and that these considerations are reflected (implicitly or explicitly) in the structure of urban experiments.

The 'surface' for the UBL is represented by the top of the UCL and considerable effort has been expended in establishing the sensible and latent heat fluxes, in particular, at this level. Observational studies have attempted to characterize different urban landscapes, yet, by their very nature, the spatial extent of their representation is restricted. To overcome these limitations, other methods have been employed using combinations of remote sensing techniques and modelling frameworks (eg, Xu *et al*., 2007; Davis *et al.*, 2008). A feature of current urban meteorological research is the extent to which observational studies are designed at a scale that is compatible with mesoscale models that can capture the larger-scale processes operating across urban areas. This is evident in studies by Freitas *et al.* (2007) and Pigeon *et al.* (2007b) on the coastal cities of São Paulo, Brazil, and Marseille, France (the UBL-ESCOMPTE project), respectively. In the case of Marseille, the research examined the extent to which a daytime sea breeze transferred heat and moisture horizontally in the layer below the measurement plane. The results indicate that, in these circumstances, including the assessment of the surface fluxes through measurement of the vertical exchanges only can underestimate Q_H by 100 Wm^{-2} and overestimate Q_E by 50 Wm^{-2}.

For many purposes, it is the UCL that is of interest – it is, after all, the zone of human occupation where decisions give rise to unique building group outcomes that affect energy exchanges and airflow patterns. Moreover, the processes and parameters at this microscale need to be distilled for deployment in city-scale models. Studies of the urban effect within the UCL formed the initial impetus for urban climate studies and this has continued. However, in addition to the urban heat island effect, other properties of the urban atmosphere are now being elucidated. George *et al.* (2007) placed three stations within the canopy layer in Baltimore, Maryland, to represent city, suburban and rural environments, respectively. Together, these stations were taken to represent an urban–rural transect. The results, after five years of observations, reveal an urban CO_2 island with concentrations in the city location higher on average by 66 ppm compared to rural settings. More generally, advances in the field have been greatly aided by the adoption of common urban configurations, such as urban canyons to represent city streets, as a means of examining urban processes (eg, Erell and Williamson, 2007). Nevertheless, there are very few comprehensive real-world observational studies of the processes operating within such environments. Offerle *et al.* (2007) report on a study of a city street in Göteborg, Sweden, that was intensely monitored. The result is a detailed depiction of the air temperature, wind and turbulence climate in the street and its relationship to ambient conditions and both urban materials and geometry. More generally, Krayenhoff and Voogt (2007) introduced a model (Temperature of Urban Facets in 3-D) designed to provide complete surface temperatures for urban areas by solving the energy budget at building surfaces. Such a model has obvious applications for the study of UCL climates and for linking indoor and outdoor thermal environments. Moreover, it can be usefully employed to 'fill in the gaps' associated with remotely sensed data that offers a partial view of these surfaces.

While the canyon approach to the study of the UCL has yielded a great deal of information that is transferable from place to place, it does not address unique urban settings. The

physical difficulty associated with observing in urban settings has restricted field experiments to relatively low-rise buildings. Concerns for the health and safety of citizens in large cities characterized by areas with very tall, closely spaced buildings has prompted a number of detailed field studies. Most notable are the Joint Urban 2003 (JU2003) and Madison Square Garden 2005 experiments, both chosen for their unique central city forms and to examine environmental 'security' issues. JU2003 was conducted from 28 June to 31 July in Oklahoma City and focused on the atmospheric dispersion of low-level releases. Twelve papers representing a cross-section of the work completed using data from JU2003 appear in a special edition of the *Journal of Applied Meteorology and Climatology* (Allwine and Leach, 2007). About half of these papers describe the wind, turbulence and dispersion in the boundary layer above and within a downtown street canyon (eg, Klein and Clark, 2007; Flaherty *et al.*, 2007; Nelson *et al.*, 2007a; 2007b). Some also examine the ability of models to capture flow patterns and predict dispersion patterns (eg, Flaherty *et al.*, 2007). Along the same lines, a special issue of *Boundary-Layer Meteorology* was given over to a series of papers produced at a NATO Advanced Research Workshop on 'Atmospheric Boundary Layers: Modelling and Applications to Environmental Security' (Baklanov and Grisogono, 2007). Hanna *et al.* (2007) examined urban field data collected from both JU2003 and the Madison Square Garden 2005 projects to extract basic scientific relations between relatively easy to observe atmospheric properties and those more difficult to obtain yet which are important for dispersion models.

While our knowledge of urban climates has progressed significantly in recent decades, unfortunately the same cannot be said with regard to the purposeful use of such knowledge. It is a great pity that the impetus for the study of urban climates and the application of findings is often inspired by crises. For example, concerns for the urban environment of Hong Kong followed the outbreak of severe acute respiratory syndrome (SARS) in 2003. The result has been the adoption of a procedure to assess the implications of planned developments on air ventilation in the city, which is characterized by relatively low velocity flows (Ng, 2007). There is evidence, however, that concerns for the urban environment generally (rather than for just air quality, for example) is becoming more common in the planning/design literature (Halwatura and Jayasinghe, 2007). In addition to general discussions on urban designs appropriate to different climates, software tools created to assist the planner for specific issues, such as the urban heat island (Sailor *et al.*, 2007), or for general urban sustainability (Robinson *et al.*, 2007) were introduced.

Finally, one area that has tremendous potential is the use of urban topographical data to examine urban microclimates at a city scale. Lindberg (2007) employs a three-dimensional model of Göteborg to explore variations in radiation receipt and to obtain sky view factors. Mobile measurements of air temperature are used to show that these digital data can be used to usefully explore intra-urban variations in air temperature.

III Conclusions

This review emphasizes research on urban climates. However, the issues raised have implications for other landscapes. The large roughness elements and great spatial diversity that characterize urban environments pose considerable difficulties for observational and modelling studies at the micro- and mesoscales. Research published in 2007 provides an oversight of developments in this field that has relevance for other climates formed over surfaces characterized by significant topographic or surface variations.

References

Allwine, J. and **Leach, M.** 2007: Editorial. *Journal of Applied Meteorology and Climatology* 46, 2017–18.

Baklanov, A. and **Grisogono, B.** 2007: Atmospheric boundary layers: nature, theory and applications to environmental modelling and security. *Boundary-Layer Meteorology* 125, 157–60.

Davis, J.C., Collier, C.G., Davies, F. and **Bozier, K.E.** 2008: Spatial variations of sensible heat flux over an urban area measured using Doppler lidar. *Meteorological Applications* 15, 367–80.

Emmanuel, R., Rosenlund, H. and **Johansson, E.** 2007: Urban shading – a design option for the tropics? A study in Colombo, Sri Lanka. *International Journal of Climatology* 27, 1995–2004.

Erell, E. and **Williamson, T.** 2007: Intra-urban differences in canopy layer air temperature at a mid-latitude city. *International Journal of Climatology* 27, 1243–55.

Flaherty, J.E., Stock, D. and **Lamb, B.** 2007: Computational fluid dynamic simulations of plume dispersion in urban Oklahoma City. *Journal of Applied Meteorology and Climatology* 46, 2110–26.

Freitas, E.D., Rozoff, C.M., Cotton, W.R. and **Silva Dias, P.L.** 2007: Interactions of an urban heat island and sea-breeze circulations during winter over the metropolitan area of São Paulo, Brazil. *Boundary-Layer Meteorology* 122, 43–65.

George, K., Ziska, L.H., Bunce, J.A. and **Quebedeaux, B.** 2007: Elevated atmospheric CO_2 concentration and temperature across an urban-rural transect. *Atmospheric Environment* 41, 7654–65.

Grimmond, C.S.B., Kuttler, W., Lindqvist, S. and **Roth, M.** 2007: Editorial. Urban Climatology ICUC6. *International Journal of Climatology* 27, 1847–48.

Halwatura, R.U. and **Jayasinghe, M.T.R.** 2007: Strategies for improved micro-climates in high-density residential developments in tropical climates. *Energy for Sustainable Development* XI(4), 54–65.

Hanna, S., White, J. and **Zhou, Z.** 2007: Observed winds, turbulence, and dispersion in built-up downtown areas of Oklahoma City and Manhattan. *Boundary-Layer Meteorology* 125, 441–68.

Klein, P. and **Clark, J.V.** 2007: Flow variability in a North American downtown street canyon. *Journal of Applied Meteorology and Climatology* 46, 851–77.

Kohsiek, W., Liebethal, C., Foken, T., Vogt, R., Oncley, S.P., Bernhofer, C. and **de Bruin, H.A.R.** 2007: The Energy Balance Experiment EBEX-2000. Part III: Behaviour and quality of the radiation measurements. *Boundary-Layer Meteorology* 123, 29–54.

Krayenhoff, E.S. and **Voogt, J.A.** 2007: A microscale three-dimensional urban energy balance model for studying surface temperatures. *Boundary-Layer Meteorology* 123, 433–61.

Lindberg, F. 2007: Modelling the urban climate using a local governmental geo-database. *Meteorological Applications* 14, 263–73.

Martilli, A. 2007: Current research and future challenges in urban mesoscale modelling. *International Journal of Climatology* 27, 1909–18.

Mauder, M., Oncley, S.P., Vogt, R., Weidinger, T., Ribeiro, L., Bernhofer, C., Foken, T., Kohsiek, W., de Bruin, H.A.R. and **Liu, H.** 2007: The Energy Balance Experiment EBEX-2000. Part II: Intercomparison of eddy-covariance sensors and post-field data processing methods. *Boundary-Layer Meteorology* 123, 29–54.

Nelson, M.A., Pardyjak, E.R., Brown, M.J. and **Klewicki, J.C**. 2007a: Properties of the wind field within the Oklahoma City Park Avenue street canyon. Part II: Spectra, cospectra and quadrant analyses. *Journal of Applied Meteorology and Climatology* 46, 2055–73.

Nelson, M.A., Pardyjak, E.R., Klewicki, J.C., Pol, S.U. and **Brown, M.J.** 2007b: Properties of the wind field within the Oklahoma City Park Avenue street canyon. Part I: Mean flow and turbulence statistics. *Journal of Applied Meteorology and Climatology* 46, 2038–54.

Ng, E. 2007: Policies and technical guidelines for urban planning of high-density cities – air ventilation assessment (AVA) of Hong Kong. *Building and Environment* 44, 1478–88.

Offerle, B., Eliasson, I., Grimmond, C.S.B. and **Holmer, B.** 2007: Surface heating in relation to air temperature, wind and turbulence in an urban canyon. *Boundary-Layer Meteorology* 122, 273–92.

Oke, T.R. 2006: Initial guidance to obtain representative meteorological observations at urban sites. Instruments and Observing Methods, Report No. 81. WMO/TD-No. 1250. Retrieved 20 August 2009 from http://www.wmo.ch/pages/prog/www/IMOP/publications/IOM-81/IOM-81-UrbanMetObs.pdf

Oncley, S.P., Foken, T., Vogt, R., Kohsiek, W., de Bruin, H.A.R., Berhofer, C., Christen, A., van Gorsel, E., Grantz, D., Feigenwinter, C., Lehner, I., Liebethal, C., Liu, H., Mauder, M., Pitacco, A., Ribeiro, L. and **Weidinger, T.** 2007: The Energy Balance Experiment EBEX-2000. Part I: overview and energy balance. *Boundary-Layer Meteorology* 123, 1–28.

Pearlmutter, D., Berliner, P. and **Shaviv, E.** 2007: Urban climatology in arid regions: current research in the Negev desert. *International Journal of Climatology* 27, 1875–85.

Pigeon, G., Legain, D., Durand, P. and **Masson, V**. 2007a: Anthropogenic heat release in an old European agglomeration (Toulouse, France). *International Journal of Climatology* 27, 1969–81.

Pigeon, G., Lemonsu, A., Grimmond, C.S.B., Durand, P., Thouron, O. and **Masson V.** 2007b: Divergence of turbulent fluxes in the surface layer: case of a coastal city. *Boundary-Layer Meteorology* 124, 269–90.

Robinson, D., Campbell, N., Gaiser, W., Kabel, K., Le-Mouel, A., Morel, N., Page, J., Stankovic, S. and **Stone, A.** 2007: SUNtool – a new modelling paradigm for simulating and optimizing urban sustainability. *Solar Energy* 81, 1196–211.

Roth, M. 2007: Review of urban climate research in (sub)tropical regions. *International Journal of Climatology* 27, 1859–73.

Sailor, D.J. and **Dietsch, N.** 2007: The urban heat island Mitigation Impact Screening Tool (MIST). *Environmental Modelling and Software* 22, 1529–41.

Watts, C.J., Scott, R.L., Garatuza-Payas, J., Rodriguez, J.C., Prueger, J.H., Kustas, W.P. and **Douglas, M.** 2007: Changes in vegetation condition and surface fluxes during NAME 2004. *Journal of Climate* 20, 1810–20.

Wendt, C.K., Beringer, J., Tapper, N.J. and **Hutley, L.B.** 2007: Local boundary-layer development over burnt and unburnt tropical savanna: and observational study. *Boundary-Layer Meteorology* 124, 291–304.

Xu, W., Wooster, M.J. and **Grimmond, C.S.B.** 2007: Modelling of urban sensible heat flux at multiple spatial scales: a demonstration using airborne hyperspectral imagery of Shanghai and a temperature-emissivity separation approach. *Remote Sensing of Environment* 112, 3493–510.