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Comparison of model-derived distribution of sensible heat flux over an urban area with radar-derived rainfall fields

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1 Introduction

Among the causes ascribed to the modification of precipitation induced by urbanisation (Shepherd et al., 2002), most studies suggest that dynamic forcing (destabilisation associated with the heat island and surface roughness) is the most significant, more so than microphysical or moisture enhancement. Urban areas modify boundary layer processes mostly through the production of an urban heat island, and by increasing turbulence through locally enhanced roughness (for a review see Collier, 2006). Results of numerical studies (see Thielen et al., 2000, and Shepherd, 2002, for example) show the impact of the surface sensible heat flux and roughness of urban surfaces on convective rain. Thielen and Gadian (1997) described a numerical study of the influence of topography and urban heat island effects on the outbreak of convective storms under unstable meteorological conditions. Analysis of data from convective storms in Northern England confirmed that the combination of effects such as sea breezes, elevated terrain and the presence of large cities has an influence on the initiation and development of convective storms. The results of the numerical study show that the presence of the Pennines, a north-south oriented ridge, could influence the initiation of convection due to its long sun-facing slopes, and to a lesser degree forced lifting along these slopes. The inclusion of urban heat island effects produces enhanced and prolonged convection, particularly downwind of the major urbanised areas.

Comparison of the two average annual rainfall maps covering NW England for 1941-1970 and 1961-1990 (Met. Office, UK), suggests an increase of precipitation over the easterly suburbs of Greater Manchester. Considering the expansion of urbanisation during the past fifty years with a significant increase on high rise buildings in the early 1970s, it is reasonable to consider whether or not these differences in rainfall may be attributed to the urban development.

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An estimate, based on the analysis of Shaw (1962), of the origins of precipitation in Northern England, shows that a considerable proportion (34% - 50%) of the total precipitation over the region of Manchester is of convective origin. We may anticipate that urban areas should have some impact on the initiation of this type of rainfall.

In this paper are presented some results from a study of the influence of an urban area on convective clouds and precipitation. Of particular interest is the degree to which spatial variations of surface heterogeneity, notably from high rise buildings, impact these phenomena, and whether the processes involved can be represented appropriately within a single-column model of surface energy balance applied on a rectangular grid.

A numerical scheme is presented based upon several published systems, principally Voogt and Grimmond (2000) and Grimmond and Oke (1999), and is developed to derive fields of surface sensible heat flux, for a range of wind and temperature, over an urban area (section 2). We compare the sensible heat flux fields derived with integrated rainfall fields derived from C-band radar data.

2 Modelling

In this section a numerical scheme will be described for deriving fields of surface sensible heat flux for a range of wind and temperature inputs over an urban area. The model is formulated for Greater Manchester, in a study area of 24km x 24km, with a grid resolution of 1km x 1km, where the bulk equations will be used and the model parameters are specified as averages over each grid square.

The surface sensible heat flux, Q_H, over the urban area is calculated by a resistance-type formulation using the difference between the radiometric surface temperature, T_R, and air temperature, T_a, (Voogt and Grimmond, 2000; Grimmond and Oke, 1999):

$$Q_H = \rho \ c_p \frac{\left(T_R - T_a\right)}{r_h} \qquad (1)$$

$$r_h = \frac{1}{k\,u_*}\left[\ln\left(\frac{z_S - z_D}{z_{0m}}\right) - \Psi_H\right] + \frac{1}{k\,u_*}\ln\left(\frac{z_{0m}}{z_{0hR,T}}\right) \quad (2)$$

$$L = \frac{-u_*^3 \rho c_p T_a}{kgQ_H} \quad (3)$$

$$u_* = k\,u\left[\ln\left(\frac{z_S - z_D}{z_{0m}}\right) - \Psi_M\right]^{-1} \quad (4)$$

Here, the parameter g (= 9,8 m s^{-2}) is the acceleration of gravity, ρ (=1,2 kg m^{-3}) is the air density, c_p (=1004 J kg^{-1} K^{-1}) is the specific heat of the air, at constant pressure, k (= 0,4) is the von Karman's constant. In this formulation, Q_H is the surface sensible heat flux, r_h is the resistance to heat transfer from a surface at the temperature T_R to an atmospheric level at the temperature T_a, L is the Monin-Obukhov length, and u_* is the friction velocity. Input meteorological variables used in the model are T_R, T_a, and the wind velocity, u. T_a and u are typically measured several metres above the surface, at the measurement height, z_s, in the inertial sub-layer where the Monin-Obukhov Similarity Theory is valid. Although the validity of Monin- Obukov similarity theory (MOST) in the atmospheric boundary layer has being questioned (Fisher, 2002) the surface sub-layer is usually studied within the framework of MOST. This will form the basis of the model to be used later to explore the impact of the heterogeneity of the urban canopy.

Input roughness parameters are the building height, z_H, and the frontal area index, λ_F. Over built areas z_H and λ_F are derived from analysis of surface form according to the Grimmond and Oke (1999) methodology, while for natural surfaces these roughness parameters are estimated using reference tables shown in the literature (for example, Grimmond and Oke, 1999, Wieringa, 1993, Brutsaert, 1982, Grimmond et al, 1998).The zero-plane displacement length, z_D, and roughness length for momentum, z_{0m}, are estimated as a function of building height, z_H, and frontal area index, λ_F, using Raupach's (1994, 1995) method. The roughness length for heat, z_{0h}, is determined as a function of z_{0m}, using the formulation proposed by Brutsaert (1982) for bluff-rough surfaces.

Stability corrections for momentum, Ψ_M, and heat, Ψ_H, are the Paulson (1970) stability functions. The Hogstrom (1988)-modified Dyer (1974) equations are used to calculate Ψ_M, when L<0, and Ψ_H. The Ulden and Holtslag (1985) equation is used to calculate Ψ_M, when L>0. Q_H, u_* and L (or the stability functions) are determined by an iteration of equations (1)- (4).

3 Case studies

Radiometric surface temperature values, T_R, are obtained from satellite observations over Greater Manchester using the MODIS/Terra and MODIS/Aqua Land Surface Temperature/Emissivity [modis-land.gsfc.nasa.gov] data. Fig. 1 shows the distribution of the radiometric surface temperature, T_R, over an area of 24km x 24km of Greater Manchester, on the clear sky study day of 14th June 2004 at 12:50 UTC, and on the cloudy day of 21st June 04 at 13:00 UTC. The spatial resolution of the satellite radiometric surface temperature is 1km x 1km.

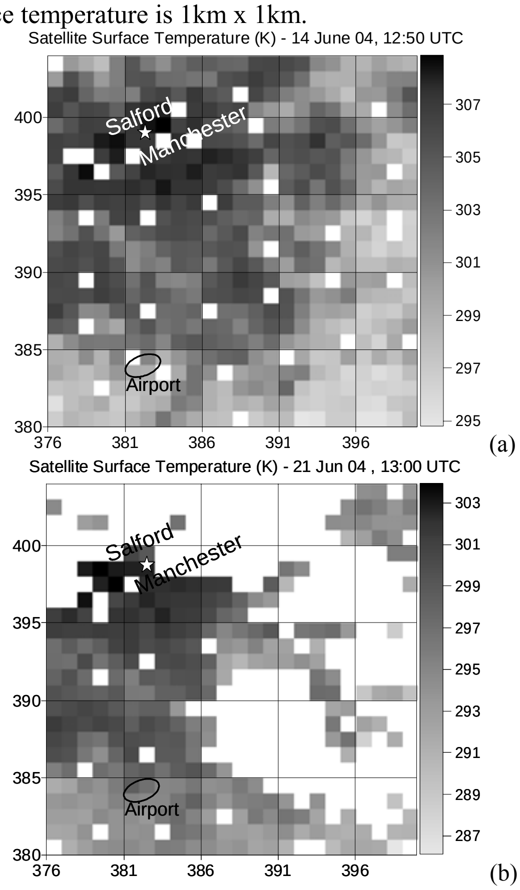

Fig. 1. Radiometric surface temperature, T_R, over Greater Manchester (24kmx 24km), from satellite imagery around 13 UTC, on the study days of 14th (a) and 21st June 2004 (b). The coordinates X and Y are the U.K. National Grid Coordinates. The legend on the right-hand sides refers to the values of the temperature expressed in K. The locations of Salford University and Manchester airport are indicated. White areas are cloud or missing data.

Model input roughness parameters, building height, z_H, and the frontal area index, λ_F, were estimated from digitalised lidar data of the elements of the surface provided by the Environment Agency and Cities Revealed (for a detailed explanation see Carraça, 2006). The values so derived were comparable to previously published work such as that described by Ellefsen (1990-1991). The values of z_H and λ_F used for the Greater Manchester study area are shown in Fig.2a and Fig. 2b respectively.

Fig. 3 gives model results for the spatial distribution of surface sensible heat flux at z_S=45m, Q_H, over Greater Manchester, on the 14th June 2004 at 12:50 UTC and on the 21st June 2004 at 13:00 UTC. As expected we found higher value of sensible heat flux over urbanised zones than over rural zones.

The spatial distribution of these fluxes follows the same patterns as the spatial distributions of the surface temperature (see Fig. 1) and roughness, z_H, z_D, and z_{0m}. A comparison of Fig.3 and Fig. 2b reveals that the fields shown have a similar pattern. However higher values of the surface sensible heat

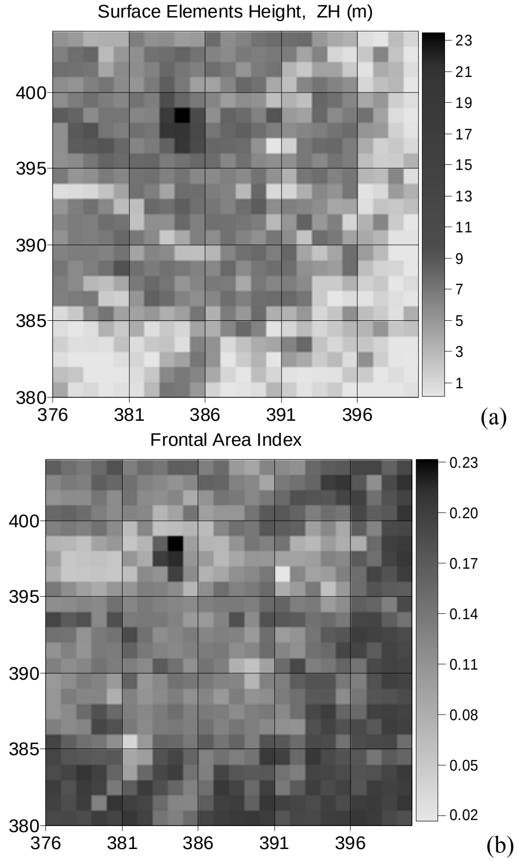

Fig. 2. (a) Mean building height, z_H, for each sector in the study area of Greater Manchester indicated in Fig.1 . The coordinates X and Y are the UK. National Grid Coordinates. The total study area is 24 x 24 km^2 and the area of each grid square 1 km^2. The legend on the right-hand side refers to the values of z_H expressed in m. (b) Mean frontal area index, λ_F , for the same study area shown in Fig.1. The legend on the right-hand side refers to the values of λ_F.

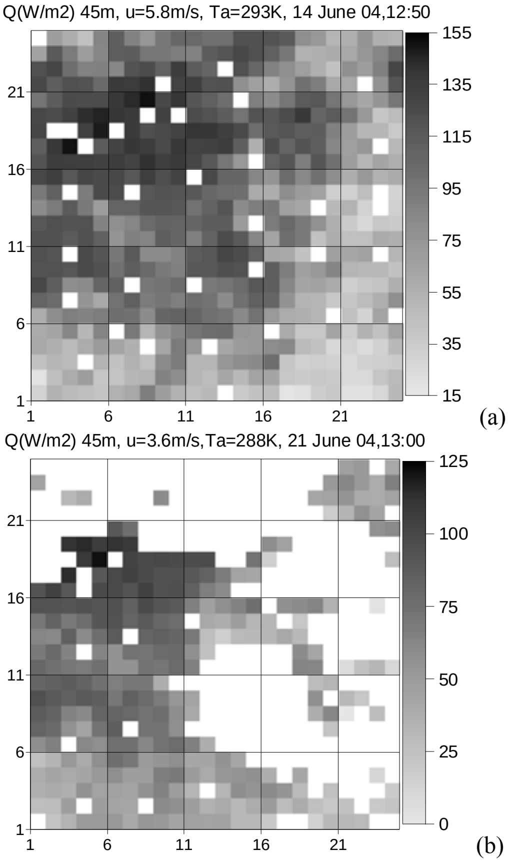

Fig. 3. Model estimates of surface sensible heat flux, Q_H, on 14th (a) and 21st (b) June 2004 around 13 UTC, for the study area Greater Manchester (24km x 24km) shown in Fig. 1. The legend on the right-hand side refers to the values of Q_H expressed in W/m^2. White areas are cloud or missing data.

flux, Q_H, occur in the urban sectors with relatively lower frontal area index, λ_F, and vice-versa. This result is in agreement with the basic model equations, and with model tests results (not shown here). While $\lambda_F < 0.29$, z_{0m} increases and Q_H decreases as λ_F increases. However, there is different behaviour of the roughness parameter z_{0m} for values of $\lambda_F > 0.29$. After this point the roughness z_{0m} is seen to decrease as λ_F increases, yet the sensible heat flux increases (z_{0h}, Q_H). λ_F values over all the study area are less than a threshold value of 0.29.

4 Initiation of convection

In unstable conditions updrafts are associated with an increase in temperature and sensible heat flux associated with the upward movement of buoyant thermals. The sensible heat flux is a measure of the vertical gradient of temperature and the lapse rate (e.g. Oke, 1987). Hence, the field of sensible heat flux relates to the occurrence of upward moving thermals in unstable conditions and therefore the likely initiation of rainfall. Hence, areas of enhanced sensible heat flux should relate to the initiation of convective showers. We next examine this in relation to the urban area of Greater Manchester.

Convective cells are shonwn to be moving across North West England in the MODIS visible satellite image at 11:14 UTC on 21st June 2004.

In order to examine the rainfall from the convective cells, data from the C-band Hameldon Hill radar located some 24km north of the city centre are displayed in Fig. 4 on Hovmoller diagrams. In these diagrams distance is plotted against time for a direction corresponding to the low level wind level direction (westerly in this case). Fig. 4a shows the diagram constructed for the period 06:00 to 12:00 UTC on 21st June 2004. Fig. 4b shows the same format for the period 12:00 to 18:00 UTC on this day. The grey scale shading indicates the rainfall rates in mm h$^{-1,}$ and the centre of each box corresponds to Manchester city centre.

During the morning (Fig. 4a) a convective cell is generated just downwind of the city centre moving in an easterly direction. In addition, cells are also seen to form on the western edge of the urban area dissipating as they move over to the east of the city towards the upland area. In the afternoon (Fig. 4b) a cell forms to the west of Manchester city centre over Salford moving eastwards and dissipating. The areas associated with the cell generation seem to be those areas in which the sensible heat flux is largest (Fig. 3) brought about by the existence of high rise buildings. It would appear that the area of Salford (high rise buildings close together) has a similar impact to medium height buildings over a larger area. Which of these areas leads to convective cell generation depends upon the details of the wind and temperature fields.

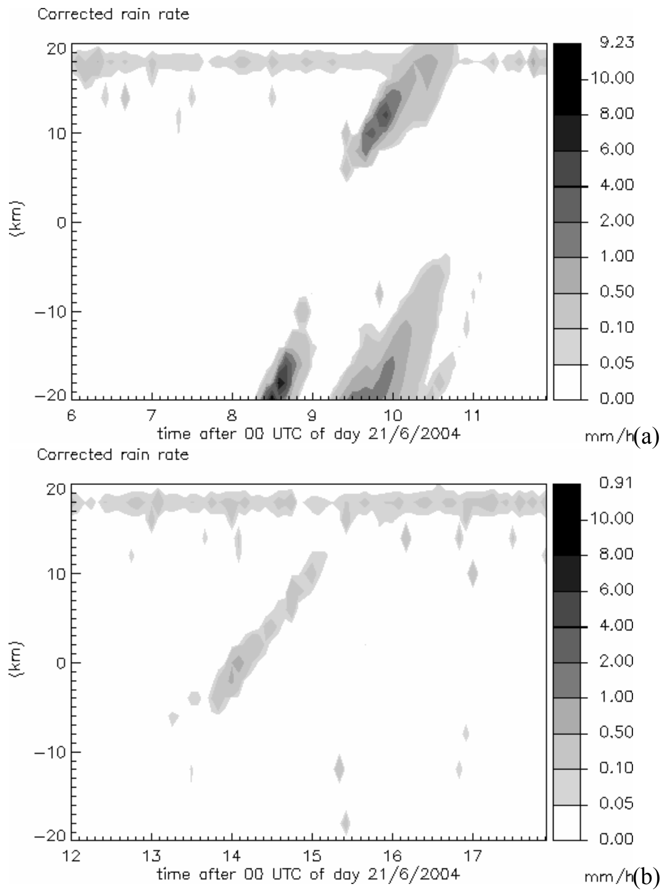

Fig. 4. Hovmoller diagrams of rainfall rate (mmh^{-1}) on 21st June 2004 derived from the Hameldon Hill C-band radar located some 24km north of the centre of Manchester, North West England (a) 06:00-12:00 UTC and (b) 12:00-18:00 UTC. The coordinates represent distance along a 7km wide swath running through the city centre in the direction of the westerly cell movement and the abscissa represents time. Some small spurious areas of rain remain where the removal of radar ground clutter echoes has been incomplete.

5 Concluding remarks

The sensitivity of Q_H to the different model parameters, T_R, T_a, u, z_H, and λ_F, has been investigated. Initial experiments aimed at examining the impact of spatial variations of roughness and stability have shown that significant variations in sensible heat flux may occur. Such variations may lead to the initiation or enhancement of convection when the boundary layer is unstable.

A case study was described in which the model-generated distribution of sensible heat flux over Greater Manchester was compared with rainfall fields derived from C-band radar. Convective cells are observed to initiate just downwind of the centre of the city occupied by high rise buildings, the exact impact of the building configuration depending upon the details of the wind and temperature fields.

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