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Buoyancy and turbulence-driven atmospheric circulation over urban areas

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ABSTRACT

In the buoyancy and turbulence-driven atmospheric circulations (BTDAC) that occur over urban areas where the approach means wind speeds are very low (less than turbulent fluctuations and typically <3 m/sec), the surface temperatures are significantly higher than those in the external rural areas, and the atmosphere above the mixing layer is stably stratified. In this paper, the mechanisms of BTDAC formation are studied through laboratory experiments and modelling, with additional low-level inflow from external rural areas and a divergent outflow in the opposite direction in the upper part of the mixed layer. Strong turbulent plumes in the central region mix the flow between lower and higher levels up to the inversion height. There are shear-driven turbulent eddies and weaker buoyant plumes around the periphery of the urban area. As the approach flow is very weak, the recirculating streamlines within the dome restrict the ventilation, and the dispersion of pollution emitted from sources below the inversion height leading to a rise in the mean concentration. Low-level air entrained from rural areas can, however, improve ventilation and lower this concentration. This trend can also be improved if the recirculating structure of the BTDAC flow pattern over urban areas breaks down as a result of the surface temperature distribution not being symmetrical, or as the approach wind speed increases to a level comparable with the mean velocity of circulation, or (except near the equator) the urban area is large enough that the Coriolis acceleration is significant.

Introduction

Since cities were first established, their leaders and communities have worked in many different ways to understand and improve their natural and social urban environments. Several studies (*e.g.*, Eliasson, 2000; Hunt et al., 2005) have identified important differences in the urban atmospheric environment, such as whether the mean winds approaching the city are significant in relation to the magnitude of local turbulence. Typical of low latitude cities, the circulation is characterised by convergent inflow in the lower atmosphere and divergent outflow at a higher atmospheric level, with turbulent plumes rising up to the inversion or mixing height. Field data, experiments and numerical simulations show that in these quasi-static conditions, the depth of the mixing layer is greatest over the central part of the city (as in London; Hunt,

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2005). This characteristic dome-shaped flow field is commonly referred to as buoyancy and turbulence-driven atmospheric circulation (BTDAC). Barlag and Kuttler (1991) and Eliasson and Holmer (1990) found that the background condition favoured by BTDAC occurs for about 10% of the year, but more so at low latitudes. The frequency of occurrence and amplitude of BTDAC in large cities can occur more frequently with different climatic and geographical conditions. Barlag and Kuttler (1991), Luo and Li (2011) and Wang and Li (2016) described the significant roles played by BTDAC in urban ventilation and urban planning. Fernando et al. (2001) proposed a new research focus on urban fluid mechanics to systematically examine fluid mechanics and contaminant dispersion in large cities.

Findlay and Hirt (1969) and Shreffler (1979) investigated urban-induced wind (also known as country breeze). However, only the convergent inflow in the lower atmosphere was detected and analysed; due to limitations on measurement, only the lower part of the BTDAC could be accessed.

The overall concept and modelling of BTDACs need improving, to account more thoroughly for the relation between the convergent flow near the urban centre but below the divergent outflow in the upper part of the mixed layer and below the inversion height, and the change in the turbulent structure from being shear dominated over the outer part of the urban area to plume dominated near the centre. Both these forms of large scale eddy motions interact and drive turbulent motions within the stratified inversion layer and also generate internal waves in the atmosphere above the inversion layer. The mean and turbulent flow vary over the day, evening and night, and has a significant effect of the diurnal variation of turbulent dispersion from local and area sources within and outside the urban area. The diurnal circulation also depends on the thermal properties of the buildings, and surfaces at and below the ground.

Recent research on BTDAC has included numerical simulations (*e.g.*, Ryu et al., 2013), field measurements (*e.g.*, Hidalgo et al., 2008b), reduced-scale models in air-tanks (*e.g.*, Noto and Okamoto, 1991), reduced-scale models in water-tanks (*e.g.*, Lu et al., 1997a; Moroni and Cenedese, 2015) and theoretical models (*e.g.*, Han and Baik, 2009; Hunt et al., 2012). The study of BTDAC mechanism can be used in pollutant concentration modelling in the urban area such as, Zhu et al. (2015), Long et al. (2016), Wang et al. (2015) and Yin et al. (2016).

1. Characteristics of BTDAC

1.1. *Quasi-steady state during day-time and night-time BTDAC*

The basic characteristics of a BTDAC over an urban area with a symmetrical distribution of surface temperature are illustrated in Figs. 1 and 2.

BTDAC consists of a convergent inflow at a lower atmospheric level, a divergent outflow at a higher level and a dome-shaped flow field resulting from entrainment and overshoot at the top of the BTDAC (Fig. 1). It is influenced by the following factors: (1) differences in heat flux between urban and rural areas; (2) background stratification, which is indicated by buoyancy frequency, *N*; and (3) urban morphology, such as the diameter of the built up region of the urban area (*D*), the roughness of the urban area (defined by z_o), building-area density and building frontal area density. During both the day, evening and the night, BTDAC is caused by a significant temperature difference between urban and rural areas. The turbulence structure depends significantly on the thermal properties of buildings and surface materials, as well as the interactions with the stable interface and the incoming rural flow.

Urban dome size determines the upper level of pollutant dispersion, as discussed in Section 4. As the energy balance in urban and rural areas varies diurnally, if the background wind speed is small, the overall BTDAC occurs over the same time scale. The force driving BTDAC is the buoyancy generated by a temperature difference between urban and rural areas. BTDAC is also affected by the magnitude and distribution of surface roughness elements, radiative exchanges with the buildings and other surface elements, and heat and momentum fluxes at the stably stratified inversion layer.

The magnitude of the self-generated BTDAC can be estimated from the overall thermal and kinetic energy balance of the atmosphere below the inversion layer, if the following assumptions are made: (1) the energy change caused by background wind is omitted; and (2) BTDAC is, for a certain period during the diurnal cycle, in a steady state, with no significant time variations of the velocity field or temperature field.

The resulting energy balance is described in Eq. (1) below:

$$E_u = E_{tur} + E_{diss} + E_r \quad (1)$$

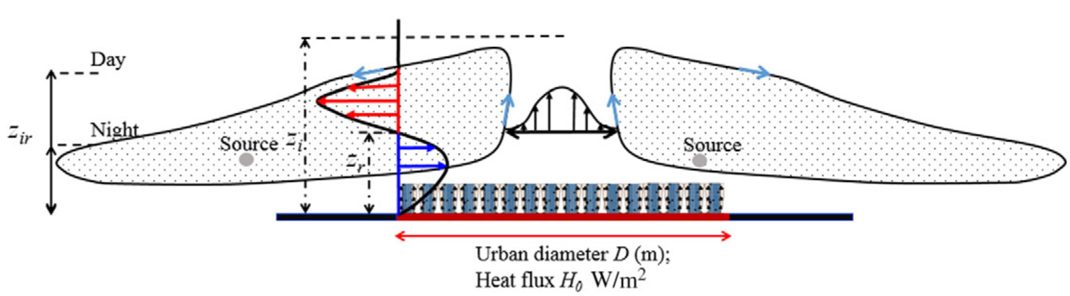

Fig. 1 – Schematic diagram of BTDAC for a two-dimensional or axisymmetric surface heating. Note that the differences in the mixing heights between the central (z_i) and external regions (z_{ir}) are larger in the evening and at night than during the day. The mean inflow is primarily driven by buoyant thermal forcing by day and by a shallow thickness gravity-current in the evening, driven inwards by the cool air from near the periphery. Also note the variation of the turbulence structure within and above the mixed layer, illustrated in Fig. 2. BTDAC: buoyancy and turbulence-driven atmospheric circulations.