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## The Canopy and Aerosol Particles Interactions in TOulouse Urban Layer (CAPITOUL) experiment

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With 12 Figures

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### Summary

The CAPITOUL experiment is a joint experimental effort in urban climate, including the energetic exchanges between the surface and the atmosphere, the dynamics of the boundary layer over the city and its interactions with aerosol chemistry. The campaign took place in the city of Toulouse in southwest France, for one year, from February 2004 to February 2005. This allowed the study of both the day-to-day and seasonal variability of urban climate processes. The observational network included surface stations (meteorology, energy balance, chemistry), profilers and, during intensive observing periods, aircraft and balloons.

The urban Surface Energy Balance differs between summer and winter: in summer, the solar heat stored during the previous daytime period is enough to maintain the heat release at night, but in winter, almost all the energy comes from the anthropogenic heat released by space heating. Both processes produce the well known Urban Heat Island (UHI).

The city is shown to impact the entire boundary layer on specific days, when an urban breeze is observed. In winter-time, fog is found to be modified due to the vertical structure of the nocturnal boundary layer above the city (which is slightly unstable and not stable).

The measurements of aerosol properties in and downwind the city permitted documentation of the urban aerosol as well as the chemical transformation of these aerosols, in particular the ageing of carbonaceous aerosols during transport. The Toulouse aerosol is mainly composed of carbonaceous particles. There is important seasonal variation in the ratio of black carbon to organic carbon, in the concentration of sulfates and nitrates and in the related radiative aerosol impacts.

SF<sub>6</sub> was released as a tracer in a suburban area of Toulouse during anticyclonic conditions with weak winds. The tracer measurements show dispersion was mainly driven by the surface sensible heat flux, and was highly sensitive to the urban heat island and also to the transport of boundary layer clouds.

Modeling was fully integrated into the campaign. Surface energy balance and urban boundary layer processes have already been used to complement the analyses of the physical processes observed during the campaign. Companion papers detail most of these observation or modeling studies.

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## 1. Introduction

Cities create their own micro- and local climates. Hence city residents are subjected to modified thermal and moisture environments as well as increased air pollution. Moreover, economic activities are concentrated in cities, so that important issues of resource use, cost and liveability are related to modified urban climates: for example the possible modification of the energy demand in terms of winter heating and of summer air-conditioning. Thus, improved knowledge of the physical and chemical processes in the urban boundary layer (UBL) is of primary importance to advance understanding of both urban climates and their impacts. Several approaches are used in the community: direct measurement, laboratory experiments, and finally modelling.

Numerous experimental campaigns have been carried out recently in urban or suburban environments. In response to societal demand, most campaigns focus on the description of air quality (e.g. MEDCAPHOT-TRACE over Athens (Klemm 1995), and ESQUIF, ESCOMPTE on Paris and Marseilles – Menut et al. 2000; Cros et al. 2004), by documenting at the regional scale the chemical emissions and pollution in the boundary layer. Knowledge of the chemical composition of urban aerosols and their related radiative impact have also been improved during these campaigns (Liousse et al. 2004; Cachier et al. 2005; Cousin et al. 2005; Mallet et al. 2005, 2006), but the coupling between aerosols and fluid dynamics was not studied.

In fact, few campaigns measure the physical, thermodynamic and even chemical processes at the urban scale. In Europe, the ESCOMPTE-UBL campaign (Mestayer et al. 2005) in and near the coastal city of Marseille (France) documented energy exchanges in a summer period (Grimmond et al. 2005), and the complex interactions between sea breezes and the urban boundary layer (Bastin and Drobinski 2005; Lemonsu et al. 2006a, b; Pigeon et al. 2006). The BUBBLE experimental campaign (Rotach et al. 2005) was conducted in Basel (Switzerland) for a period of a year. Detailed measurements were carried out within the urban canopy, providing advances to knowledge of the structure of turbulence in street canyons and on the annual cycle of the energy balance. These continuous

measurements were supplemented by urban boundary layer sampling using profilers and a tethered balloon during a month-long period of intensive observation in the summer. The combined measurements made it possible to document turbulence within the urban boundary layer. Because of the geography of the two cities – Marseille is a coastal city, Basel is located in an alpine valley – the flow within the boundary layer is mainly generated by topographic circulations (sea-breeze and slope-breeze, respectively) rather than by the city itself. A main reason for the CAPITOUL campaign was therefore to focus on a city where the flow in the atmospheric boundary layer, during anticyclonic conditions, is significantly influenced by the city itself.

In the United States, two recent field projects have examined the detailed flow characteristics in cities: URBAN 2000 in Salt Lake City (Allwine et al. 2002) and more recently Joint-Urban 2003 in Oklahoma City (Allwine et al. 2004). The principal scientific objective of these studies was to study pollutant dispersal in central city areas, in order to build modelling and intervention strategies in the event of chemical or biological terrorist attacks. These campaigns were based on passive tracers ( $\text{SF}_6$ ) released at various sites. Observations were made using surface instrumentation, remote sensing and helicopters. Modelling and data assimilation (to improve in real time the field of wind in the dispersal models) studies were also included in these campaigns.

Numerical modelling is an efficient tool for studying urban micro- and local climates for several reasons. Firstly, when coupled with experimental studies, it permits better understanding of the processes because whilst observations are limited, in space, time and the nature of the observed quantities, modelling can help to fill these gaps, through the resolution of complete physical equations. When observations are limited to a few stations or along an aircraft flight path, modelling can simulate the fuller spatial and temporal evolution of the 3D boundary layer. For example, modelling allowed Sarrat et al. (2006) to study the interaction processes between nocturnal UBL specific turbulence and Nox/Ozone chemistry. Secondly, models can be used to characterise conditions in cities other than where observations have been made (assuming

the model has been validated against such observations), in order to study the urban climates anywhere. A review of recent modelling studies of urban climate is presented by Masson (2006).

The present paper introduces an experimental campaign dedicated to the study of urban climate in Toulouse: the processes causing it, their effects, and their intra-annual variability. It is called the Canopy and Aerosols Particles Interactions in Toulouse Urban Layer (CAPITOUL) experiment. Section 2 presents the objectives, Sect. 3 outlines the experimental network and Sect. 4 summarizes some of the initial results, most being detailed in separate papers in this issue of *Meteorology and Atmospheric Physics*.

## 2. Objectives of the campaign

The CAPITOUL campaign aims to quantify the effects and causes of the interactions between the urban surface, the development and 3D-structure of the urban boundary layer (UBL) and of urban aerosols, on the scale of the city down to the scale of the districts. Unlike the BUBBLE campaign it is not the aim to document turbulence within the canopy, but rather to quantify the role of the city (by its turbulent exchanges above the urban canopy) on the UBL, and the urban-generated air circulation that develops within the UBL (both urban breeze and urban plume). The focus is on the description and analysis of the influence of the city on the boundary-layer circulations, especially during anticyclonic situations. In order to show significant urban effects on flow, the city needs to be away from areas influenced by mountain or sea-breezes. This study emphasizes description and explanation of the temporal variability of the processes during an annual cycle. It also incorporates modelling aspects, with a view to improving the research and weather forecast models for cities.

More precisely, the objectives of CAPITOUL are as follows:

### 2.1 Comprehension of urban surface – atmosphere exchanges

Energy exchanges at the surface can be written, according to Oke (1988):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1)$$

where  $Q^*$  is the net all-wave radiation (due to both solar and infra-red radiation exchanges),  $Q_F$  is the anthropogenic heat releases related to human activities,  $Q_H$  is the turbulent flux of sensible heat between the surface and the atmosphere (by convention here  $Q_H$  positive is a gain for the atmosphere),  $Q_E$  is the turbulent flux of latent heat which is due to evaporation and condensation of water at the surface,  $\Delta Q_S$  is the net energy storage uptake by or released from surfaces (buildings, roads, soils) and  $\Delta Q_A$  is the flux related to temperature advection by the horizontal air flow below the canopy top. The advective flux can be significant in the presence of strong horizontal gradients within the boundary layer, as in the immediate vicinity of the coast (1 km) in condition of sea breeze (Pigeon et al. 2007a). Over Toulouse, advection plays a role at the scale of the whole boundary layer (it does for urban breeze or urban plume), but it does not modify the energy exchanges in and at the immediate vicinity of the canopy: these exchanges are in quasi-equilibrium with the atmospheric conditions in the inertial surface layer. In that case the energy balance reduces to:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S \quad (2)$$

The objective is to document these energy exchanges, and their causes, during an annual cycle. Some of the most interesting aspects are:

- description of the various fluxes in a variety of weather conditions, continuously over a year,
- estimation from energy consumption of anthropogenic flux  $Q_F$ , from the tower measurements
- behaviour of evaporation after rainy conditions
- modelling these fluxes

From these data, a complementary and innovative objective is to measure the turbulent processes of transfer of urban aerosols from the canopy towards the atmosphere and both their chemical composition and microphysical properties.

### 2.2 Structure and development of the urban boundary layer

A principal goal of CAPITOUL is to quantify thermodynamical processes and surface-atmosphere interactions within the UBL. The experimental design thus spatially explores the

boundary layer using aircraft-based measurements, in addition to surface measurements. Moreover, the diurnal evolution of the UBL is studied for various seasons, focusing on anticyclonic conditions with weak winds. Particular interest is focused upon:

- the structure and evolution of the Urban Heat Island (UHI) and the humidity field are measured including their intra-urban structure and the vertical structure of the nocturnal boundary layer above the city.
- the dynamic and thermodynamic impact of the city on the urban boundary layer is observed, in order to demonstrate the urban breeze system and the urban plume.
- the impact of the city on fog formation, development and dissipation, due to the additional warmth of the nocturnal boundary layer is studied. In order to do that the spatial extent of urban and rural fog and their thermodynamic characteristics are observed.

### 2.3 Transformation of urban aerosols

One of the aims of this project is therefore to better understand the links existing between the dynamic properties of the UBL on the one hand, and the chemical properties and microphysics of aerosols during their residence in the atmosphere on the other. To this end, it is essential to document correctly the way in which the pollutants are transported, mixed and aged in the UBL. This study is therefore subdivided into four aspects:

- physical-chemical characterisation of the urban aerosol. This includes the chemical speciation of the urban aerosol near the source, including the mineral and organic composition of the particles, in relation to its granulometry, optical and hygroscopic properties.
- ageing of the urban aerosol. Characterisation of urban aerosol also requires studying the evolution of their physical-chemical properties following their initial emission into the UBL.
- radiative impact of the urban aerosol. One of the greatest sources of uncertainty in the prediction of the development of the urban climate probably is that related to the uncertainties involved in estimating the radiative forcing due to aerosols. These uncertainties should be re-

duced when more precise information on the first two aspects is obtained.

- vertical transport. Vertical transport processes play an important role in both ventilating pollutants emitted at the urban surface into the atmosphere and introducing pollutants emitted aloft down into street canyons, determining not only pedestrian exposure, but also the impact of urban-based particle emissions on urban and regional climates.

### 2.4 Heterogeneity of urban surface temperatures

Urban surfaces, due to their heterogeneous structure at small-scale (the orientation and material make-up of the surfaces), warm up very differently. This induces strong spatial heterogeneity of surface temperatures (Voogt and Oke 1997, 2003). This character influences heat exchange with the atmosphere (Voogt and Grimmond 2000). Another impact is the strong directional anisotropy in the thermal infrared (TIR) which has been characterized in previous experiments in Vancouver (Voogt and Oke 1998) and Marseille in summer conditions (Lagouarde et al. 2004). TIR airborne measurements were performed over the city of Toulouse and surrounding areas during CAPITOU using two cameras with the intent (i) of documenting anisotropy in conditions not met previously in winter and at night in particular (Lagouarde and Irvine, 2008, this issue), and (ii) of to study the surface heat island.

### 2.5 Short distance dispersion

Knowledge of the dispersion of gases and particles in the atmospheric boundary layer is essential in many environmental studies. Dispersion modelling becomes a high priority in an emergency response framework when there is an accidental release: for example, the AZF explosion on September 21st 2001 in a suburban area of Toulouse. Météo-France and IRSN (Institut de Radioprotection et de Sûreté Nucléaire) are involved in the national crisis cell when an accidental release occurs. The CAPITOU campaign provides an excellent experimental setting to validate modelling systems used for emergency response of short distance (a few kilometres) contaminant dispersion, because of the availabil-

ity of a complete description of the urban surface and boundary layer thermodynamics, together with SF<sub>6</sub> passive tracer dispersion measurements. The objective is to study dispersion in the boundary layer of a suburban area, since this is where industrial activities are most often located. When the surface heat flux is large, turbulence is dominated by large eddies or thermals with scales comparable to the boundary layer depth and the sensible heat flux at the surface plays a dominant role in maintaining the turbulence structure. It is thought that it is this structure that is responsible for special dispersion patterns, as shown by laboratory experiments (Willis and Deardorff 1976).

### 3. Experimental network

#### 3.1 Measurement strategy

The CAPITOU experiment was carried out from the beginning of March 2004 to the end of February 2005 in and over the city of Toulouse (43°3' 19° N, 1°26' 34° E). The urban area covers an area approximately 20 km across and encompasses 0.9 M inhabitants. A European city of this size is considered likely to generate an urban heat island of about 8° (Oke 1987) under optimum conditions, as well as city-induced three-dimensional air flow in the boundary layer.

Toulouse was chosen for several reasons:

- the city is relatively isolated from significant relief and coastlines, so that it is not influenced by local effects of valley or sea breezes. Small hills of less than 100 m elevation are present in the south-east part of the city. The meteorology is therefore mainly controlled by the synoptic flow, so in anticyclonic conditions, urban effects such as the urban heat island, an urban plume or an urban breeze circulation can develop.
- the old downtown area, with an area of approximately 3.5 km<sup>2</sup>, is relatively homogeneous in terms the building height (approximately 20 m) and construction materials (red brick walls and tile roofs) (Fig. 1). These characteristics suggest it favours the study of turbulent transport flows for a dense downtown area.



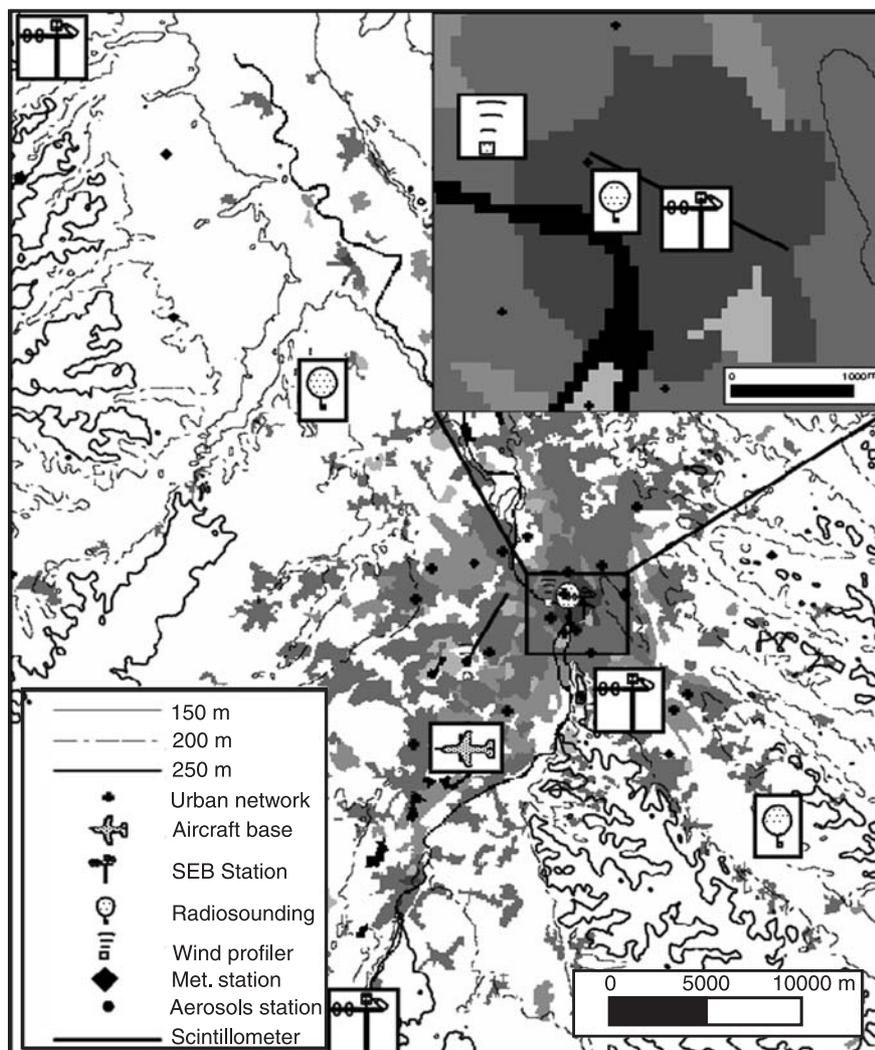
**Fig. 1.** View of Toulouse downtown roofs from the terrace of the central site

- the city has few polluting industries, the main economic activity being mainly space and aeronautics. The principal sources of air pollutants are the motor vehicle and space heating of buildings. This aids specific study of carbonaceous aerosols and sulphates. Furthermore, the relatively high insulation of the city, located in the south of France, allows us to study the impact of photochemistry on the aerosols.
- the Centre National de Recherches Météorologiques and other partners (Laboratoire d'aérodynamique, Laboratoire des Mécanismes et Transferts en Géologie and ORAMIP local air quality agency) are located in Toulouse which facilitates logistical aspects and the availability of a more comprehensive instrumentation. In particular, an instrumented aircraft is based in Toulouse, making it possible to carry out airborne measurements above the city when anticyclonic conditions appeared.

The experimental network includes fixed instrumentation that provides continuous observations and hence a complete annual time series of various processes (turbulent exchange, UHI, chemical composition of the aerosols, etc.). The measurement sites are briefly described in the Table 1 and Fig. 2. The experimental network is complemented during Intensive Observing Periods (IOPs), by airborne observations (aircraft, balloons), in order to document the three-dimensional structure of the urban boundary layer. The additional instrumentation deployed during IOPs is presented in Table 2. The 17 IOPs each lasting one or two days took place in different seasons in order to sample the annual cycle.

**Table 1.** Overview of the measurements during the one-year period of the CAPITOUL experiment. Grey shading indicates the periods when instruments are operational and data are validated

	2004												2005		
	03	04	05	06	07	08	09	10	11	12	01	02			
Energy fluxes (downtown)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Energy fluxes at canyon top (downtown)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Energy Fluxes (sub-urban)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Energy fluxes (countryside)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Aerosols (filters)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Aerosols (microphysics)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Aerosols (radiative properties)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Aerosols (fast counters)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Downtown Scintillometers	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Fixed IRT sensors	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Urban stations network	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Countryside met. Stations	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
UHF radar, ceilometer (downtown)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Sodar (suburban)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■



**Fig. 2.** Overview of the CAPITOUL experimental network in and around the city of Toulouse

**Table 2.** list of Intensive Observing Period (IOP), describing the related main objective of the IOP (UBL: UBL structure; IRT: Infra-Red surface anisotropy; Fog: urban fog; SF<sub>6</sub>: dispersion study), as well as the extra instrumentation used. Grey indicates periods when instrumentation are operational and data validated

IOP number	1	2	3	4	5	IRT1	IRT2	IRT3	6	7	8	9	10	11	12	13	14
Objective(s)	UBL	UBL SF <sub>6</sub>	UBL SF <sub>6</sub>	UBL	UBL SF <sub>6</sub>	IRT	IRT	IRT	Fog	Fog	UBL	Fog	Fog	UBL Fog	UBL	UBL	UBL IRT
date	2/3 March 2004	9/10 March 2004	26/27 June 2004	30 June 2004	1to4 July 2004	15 July 2004	29 Sept 2004	3/4 Oct. 2004	23/24 Nov. 2004	26 Nov. 2004	13 Dec. 2004	5 Jan. 2005	7 Jan. 2005	14 Jan. 2005	3/4 Feb. 2005	9/10 Feb. 2005	24/25 Feb. 2005
Urban RS																	
Countryside RS																	
Aircraft met.																	
Aircraft aerosols																	
Instrumented car(s)																	
Urban Aerosols																	
Urban CCN counter																	
Countryside aerosols																	
Surface SF <sub>6</sub>																	
Aircraft SF <sub>6</sub>																	
Daytime IRT flights																	
Nighttime IRT flight																	
Hand-held IRT																	

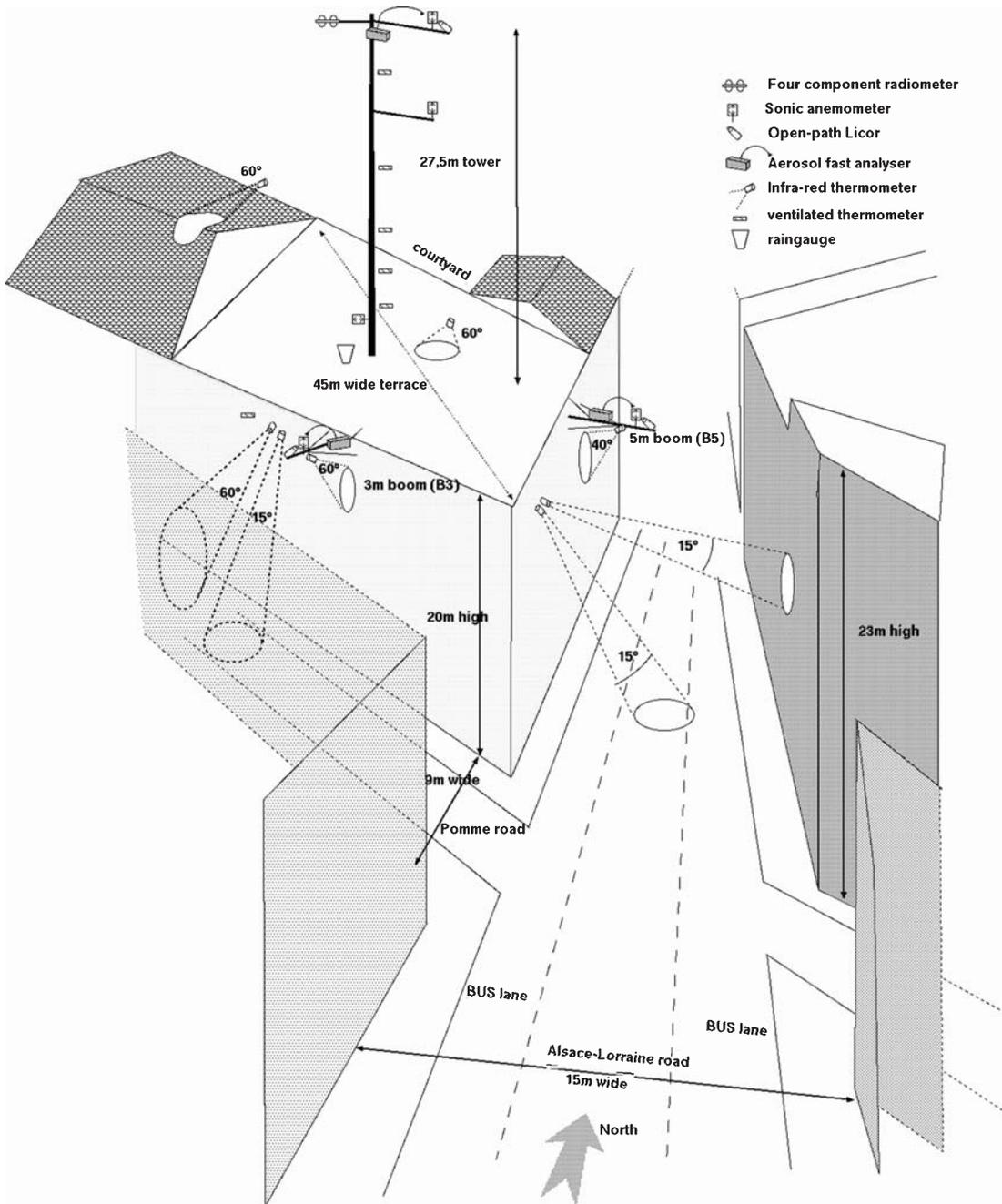
### 3.2 Year-long measurements

#### 3.2.1 Dense urban site

In order to document the surface-atmosphere energy exchange processes in the old downtown area of Toulouse, an observation site was installed there (schematised in Fig. 3). Sensors were mounted on a pneumatic tower (Hilomast NX30) to monitor the radiative and convective terms of the surface energy balance. The radiative fluxes were measured using radiometry and those of sensible heat, latent heat (evaporation) and carbon dioxide by eddy covariance techniques (Fig. 4 left). The base of the mast was on a roof at a height of 20 m, with the top of the mast being 47.5 m above the road. The turbulent instrumentation on the mast is described in Table 3. Six resistance thermometers (PT1000 Ohm) in Gill ventilated shields were installed at intervals up the mast. An additional temperature sensor is installed at the top of the adjacent street canyon (rue Pomme). The thermometers were calibrated to a precision of 0.1 °C. During operations the mast height was adjusted according to the wind speed: 47.5 m for winds < 70 km h<sup>-1</sup>, 38.5 m for winds 70–90 km h<sup>-1</sup>, and 26 m winds > 90 km h<sup>-1</sup> or for storm situations. Precipitation was measured by optical and tilting bucket rain-gauges. The advantage of the optical rain-gauge is that it provides good detection of the beginning and end of precipitation.

The Pomme and Alsace street canyons, adjacent to the mast site, were equipped with instrument booms which project above the street canyon. The booms were instrumented with turbulence sensors and optical particle counters (OPC model GRIMM 1.108, operating in fast-response mode to measure the 0.3–2.0 μm size fraction) (for details see Table 3). The booms extend across approximately one third of the width of the street away from the canyon wall (5 m for rue d'Alsace (Fig. 4 right) and 3 m for rue de Pomme). These two streets (aligned S–N and SE–NW) and another street (directed NE–SW) were equipped with infrared radiometers (Everest), to observe the surface radiation temperature of the vertical walls and the roads. All the instruments were sampled and recorded by two data acquisition computers (PCs) running Linux and supervised remotely using an Internet high-speed connection.

A large aperture scintillometer was operated in the city centre between March 2004 and February 2005. These instruments have shown good promise in urban areas of Tokyo (Kanda et al. 2002), Basel (Roth et al. 2006) and Marseille (Lagouarde et al. 2004). The aim was to further validate the method of using scintillometry to assess urban heat fluxes, particularly in winter conditions. The scintillometer used is an optical (0.93 μm) large aperture model (15 cm diameter) built by Wageningen University (Netherlands). The emitter and the receiver were

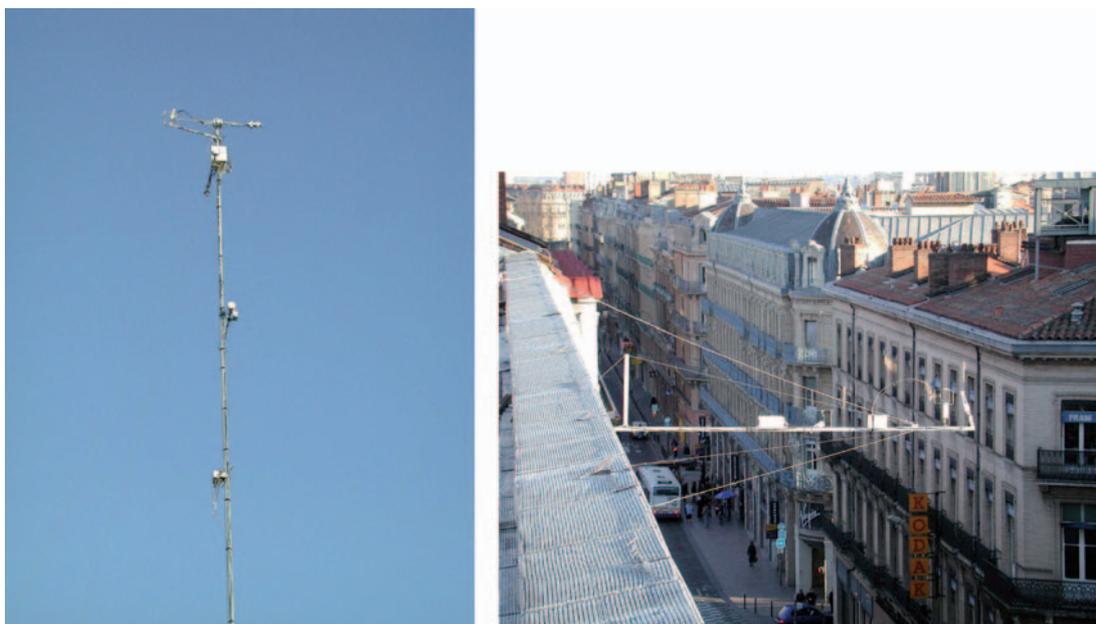


**Fig. 3.** Schematic view of the central site

installed on the roofs of two high buildings resulting in an average optical beam height of about 15–20 m above the mean roof level over a path length of 1832.5 m. The set-up was chosen so that the central mast site was near the middle of the optical path in order to compare sensible heat fluxes obtained by this method and by the classical eddy covariance method. Moreover, a special configuration was also installed during the first few months of the experiment: it consists

of associating one emitter with two similar receivers very close to each other to determine the transverse wind speed (Churnside 1992). The results of this configuration are also investigated.

The aerosol measurements were conducted in the city centre, on the roof of the central post office, approximately 20 m above the level of the road. An exhaustive size-resolved chemical speciation of the aerosols including mineral aerosol, organic aerosol and trace elements (Calvo



**Fig. 4.** Left: the pneumatic tower for surface energy balance observations; Right: 5 m turbulence-aerosol measurement boom at the top of Alsace-Lorraine street canyon

**Table 3.** Summary of surface energy balance measurements

	<b>Turbulence</b>	<b>Radiation</b>	<b>Temperature</b>	<b>Humidity</b>	<b>Particules</b>	<b>Precipitation</b>
City center (mast top)	Sonic Gill HS 50 Licor 7500 Grimm 1.108	CNR1 Kipp and Zonen	HMP232 Vaisala	HMP232 Vaisala	Grimm 1.108	qualimetrics and optical rain gauge ORG115
City center (mast intermediate)	Sonic Gill HS 50					
City center (mast bottom)	Young 81,000					
City center	Sonic Young 81,000		P 1000 Ohm		Grimm	
Pomme street boom	Licor 7500				1.108	
City center	Sonic Young 81,000				Grimm	
Alsace street boom	Licor 7500				1.108	
Suburban site	Sonic Metek	Schenk	PT 100 Ohm	HMP45 Vaisala		
Université	USA1					
Paul Sabatier	Krypton KH20					
Rural site	Aerodynamical	Schenk	PT 1000 Ohm	HMP45 Vaisala		qualimetrics
Le Fauga	method					
Rural site	Sonic Gill R2	CNR1 Kipp and Zonen	PT 1000 Ohm	HMP45 Vaisala		qualimetrics
Saint Sardos	Krypton KH20					

et al. 2008, this issue) was established from filters in two particle size ranges (PM<sub>10</sub> and PM<sub>2.5</sub>). Weekly sampling was carried out. At the same time, the total number concentration of aerosol particles with sizes ranging between a few nanometers and a few microns was measured by using a condensation particle counter (CPC model TSI 3010). The routine measurements of PM<sub>2.5</sub> and PM<sub>10</sub> made by the ORAMIP local air quali-

ty agency (<http://www.ORMIP.org>) provide further data from many other sites in Toulouse that extend the measurements made here.

### 3.2.2 Suburban site

In order to study the variability of energy exchanges in urban areas, an additional surface energy balance station was installed on a 17 m

**Table 4.** Summary of surface and mobile meteorological stations

	Temperature	Humidity	Wind	Radiation	Precipitation
Urban micro-stations network	rotronic hygroclip (2 m)	rotronic hygroclip (2 m)			
Urban micro-stations network	rotronic hygroclip (2 et 6 m)	rotronic hygroclip (2 et 6 m)			
Mondouzil	PT 1000 Ohm (2 m)	HMP45 Vaisala (2 m)	Young (10 m)	Schenk (2 m)	qualimetrics
Launac	PT 1000 Ohm (2 m)	HMP45 Vaisala (2 m)	Young (10 m)	Schenk (2 m)	qualimetrics
Auzeville	PT 1000 Ohm (2 m)	HMP45 Vaisala (2 m)	Young (10 m)		qualimetrics
Instrumented cars	PT 100 Ohm (2 m)	HMP45 Vaisala (2 m)			

high roof in a suburban area in the south-east part of Toulouse. Turbulence and radiation flux measurements were made using instruments mounted on a 10 m mast. The instrumentation is described in Table 3.

### 3.2.3 Rural sites

Toulouse is mainly surrounded by agricultural land, mostly cereal fields. Two rural sites were equipped to document the behaviour of the surface energy balance of the countryside. This was a necessary step to gauge the perturbations induced by the city compared to the rural environment. The Fauga site (Poutier et al. 2002), located 15 km to the south of Toulouse, is typical of grassland. The instrumentation at this site is described in Table 3. The Saint-Sardos site, 40 km to the NW of Toulouse (De Rosnay et al. 2006 and Table 3), was located in a maize field. These two sites were equipped to monitor soil humidity and soil temperature. Three other sites were equipped with instruments to monitor basic weather conditions (Mondouzil, Auzeville, Launac) and radiation fluxes (Table 4).

A solar photometer (CIMEL) was installed at the Fauga site as part of the AERONET/PHOTONS measurement network, to consider certain optical microphysics and properties of aerosols in the atmospheric column. This automatic photometer measures direct solar brightness at four wavelengths every 15 min in order to calculate the aerosol optical depth (AOD) and its spectral dependence (Angström coefficient). Measurement of the sky brightness also makes it possible to deduce the equivalent granulometric distribution for the atmospheric column. These parameters are used to calculate the single scattering albedo. The data are available on the site [aeronet.gsfc.nasa.gov](http://aeronet.gsfc.nasa.gov).

### 3.2.4 Mini-station network

A network of 21 temperature and humidity measurement sites is installed in various districts representative of the urban area. These stations provide continuous measurements for the duration of the experiment to aid analysis of the urban heat island and horizontal structure of the urban moisture field. Instruments were mounted 6 m above the road surface. The instrumentation is described in Table 4. A suburban site was also equipped with instruments at two levels (2 and 6 m), to consider the vertical variation of temperature and humidity.

### 3.2.5 Profilers

An UHF radar was installed in the downtown area to continuously measure the wind profile above the city. At the same site a modified ceilometer (VAISSALA CT25K) simultaneously observed the development of the boundary layer from the reflectivity of water vapour and aerosols.

### 3.2.6 Inventory of urban land use and energy use

An inventory of the energy consumption for the period of the campaign was conducted at the city scale (Pigeon et al. 2007b). This inventory takes account of releases from traffic, electricity, gas and other energy use (fuel oil, wood, coal use are minor in Toulouse). Traffic data were provided by the Transport Service of Toulouse and by the urban planning agency of Toulouse. This includes the daily traffic realised over the year by section of lane (typically 200 m). These data are available in a geographic information system (GIS). Moreover, a permanent network of 21 sensors provides hourly traffic counts, which provides the temporal variability of traffic flows.

For electricity, load carried every 10 minutes for the 14 lines serving the city were available. For gas, the daily consumption by the whole city was provided. Finally, statistical data were provided regarding consumption by other energy uses. This data set was analysed in relation to the characteristics of land use (Masséra 2005) and an inventory of energy consumption was established at a horizontal resolution of 100 m.

### 3.2.7 Laboratory analysis of the radiative properties of materials

In order to interpret the energy and atmospheric data, and to conduct the modelling, a characterisation of the building/road materials occurring in Toulouse was completed. A dedicated database was created, to give simultaneous information in three domains: a list of the main materials present in the city, the optical properties of each (spectral and directional) and their spatial variability in a given class. The spectral range covers the entire optical domain from the visible to infrared wavelengths (Briottet et al. 2006).

Measurements were conducted with an ASD spectroradiometer (400–2500 nm) at 20 cm resolution for outdoor measurements, and with a goniometer for bidirectional laboratory measurements at the same spatial resolution. A database of about 550 individual spectra was created. In the infrared domain (3–14  $\mu\text{m}$ ), a SOC 400 spectroradiometer was used at a 1.27 cm spatial resolution and a database of about 100 individual spectra was created. All spectra can be divided into 4 classical urban classes: road, pavement, paving materials used in public squares and wall. For each class, the spatial variability of urban materials has been quantified (Lachéradé et al. 2005).

Furthermore, to achieve a complete material classification over an entire urban area, an airborne campaign was conducted using a high spatial (20 cm) and high spectral (eight bands) image sensor. To this aim, a new code, ICARE, was developed to estimate the ground optical properties whatever the irradiated ground conditions. This model takes into account the relief, the spatial heterogeneity of the scene and atmospheric effects (Lachéradé et al. 2008, this issue).

## 3.3 Intensive observation periods

### 3.3.1 Airborne measurements

To document the urban boundary layer at fine spatial resolution, an instrumented Piper-Aztec twin-engine aircraft made flights above the Toulouse urban area. During an IOP, flights were made in the morning (i.e. at the time of boundary layer growth), and during early afternoon, at times when conditions favour development of urban effects in the boundary layer (as shown by the numerical study of Lemonsu et al. (2002) on the urban breeze on Paris). The aircraft flew flight legs at constant heights (150 m, 1100 m, 1700 m in summer; 150 m, 1100 m in winter) above the downtown area, and these were supplemented by pseudo-vertical soundings above the countryside. The length of the flight legs is approximately 100 km in the main wind direction and 50 km in the transverse direction. In this way the fields of horizontal wind (with a  $0.5 \text{ m s}^{-1}$  precision), temperature, humidity and pressure were measured at several heights in the boundary layer. Given the speed of the aircraft and the sampling frequency of 1 Hz, the spatial resolution is equivalent to about 70 m.

Aerosol measurements were also performed onboard the aircraft. These measurements together with the surface ones enable description of the development of the physico-chemical and radiative properties of aerosol according to altitude and distance from source. The airborne measurements also facilitate study of the ageing of the urban aerosol by measuring the Angström coefficient using a 3-wavelength nephelometer. Measurements of ozone and black carbon concentrations, and the aerosol particle counts, help to locate and characterize the urban plume. These data which describe the 3D-field of aerosol concentration and/or extinction also provide better input for radiative transfer studies.

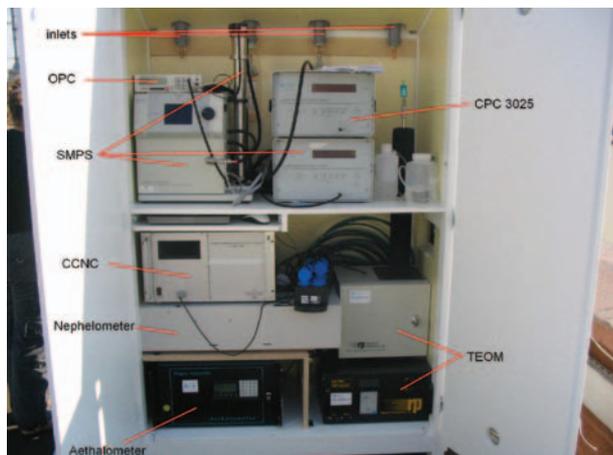
The airborne measurements are complemented by radiosoundings (Vaissala-92GPS probes), released simultaneously from two sites: a courtyard in the historical downtown area, and a rural site 20 km upstream from the downtown area (according to the wind direction, a site to the NW or the SE is used). Up to 5 urban–rural radiosounding pairs are conducted on IOP days, including night-time, dawn, morning, midday, and afternoon or evening soundings. The simul-

taneous measurement of urban and rural soundings allows quantification of (i) the daytime temperature or height difference between urban and rural boundary layers, and (ii) the nocturnal thermal structure (intensity of the inversion, height of the mixed layer downtown), intensity of the UHI with height, and the so-called “cross-over” effect (i.e., when air over the UHI during the night is colder than at the same height over the surrounding countryside).

### 3.3.2 Aerosol measurements

In the central city area, various instruments allowed us to retrieve the different aerosol properties (Gomes et al. this issue; Calvo et al. this issue). Aerosol particles were collected on filters in three size class (PM 1, PM 2.5 and PM 10) for chemical analysis of mineral, organic and trace element fractions. In addition, the mass concentration of PM 2.5 was monitored with a TEOM. The aerosol size distribution was obtained from a SMPS and an OPC for the particle size range between 15 and 600 nm and between 0.3 and 20  $\mu\text{m}$ , respectively. The optical properties (scattering and absorption) were measured by combining a nephelometer and an aethalometer. Finally, information on the hygroscopic properties of the particles also could be obtained episodically using a cloud condensation nuclei counter (Fig. 5).

During the summer IOP (25 June–10 July), a mobile laboratory instrumented for measure-



**Fig. 5.** Instruments to monitor the physical and radiative properties of the aerosols during CAPITOUL IOPs on the roof of the Toulouse central Post Office (see text for details)

ments of gases ( $\text{CO}$ ,  $\text{O}_3$ ,  $\text{SO}_2$ ) and aerosols (filters for aerosol chemical speciation, optical counter for aerosol size and nephelometer and aethalometer for optical properties) was installed at Escalquens (SE of Toulouse), in order to study the ageing of urban aerosols downwind of Toulouse.

### 3.3.3 Instrumented vehicle

Two light vehicles were instrumented with temperature and humidity sensors in ventilated shields and to measure roadway temperature (Everest radiometer). The vehicles included a GPS to geo-locate the measurements. The instrumentation is described in Table 4.

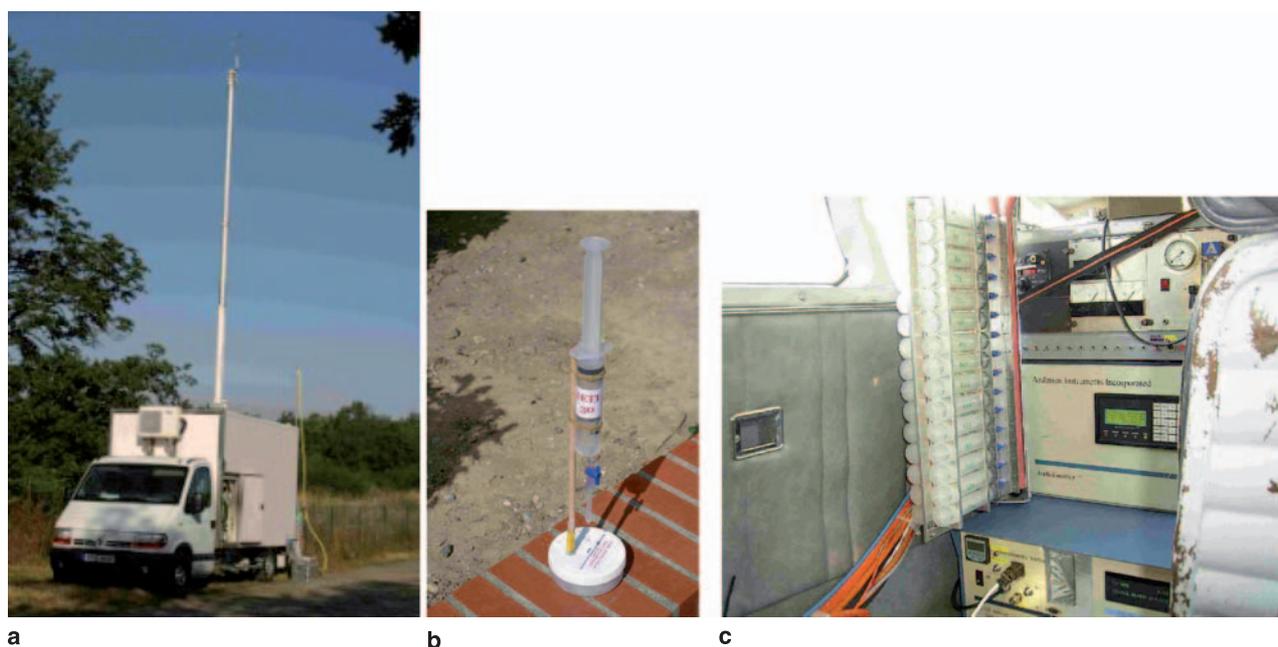
### 3.3.4 Thermal infra-red measurements

Thermal infra-red (TIR) measurements were performed using 2 TIR cameras (INFRAMETRICS M740 and FLIR SC2000), placed onboard the aircraft with backward inclinations of 10 and 50°. At the aircraft operating altitudes, the two cameras provide a spatial resolution ranging between 2 m and 6 m, and 1.5 m and 3 m, respectively. Several short flight legs at 300 m above the surface were flown in different directions centred on the city centre. In order to document the diurnal and seasonal variability of surface temperature, dedicated TIR flights were done in summer, autumn and winter, in the morning, afternoon and at night. The night-time flights are relatively novel and allow study of the impact of anthropogenic heat on surface temperature heterogeneity in winter.

Furthermore, in order to retrieve surface temperatures from the aircraft imagery, radiosoundings were done once during each flight (from the city center), and ground truth surface temperature measurements (see Sect. 3.2.1) were completed using hand-held infra-red thermometers (Minolta/Land Cyclops Compac 3 IR thermometer) on roads, walls and some roofs on several blocks in the city centre.

### 3.3.5 $\text{SF}_6$ measurements

The tracer dispersion campaign took place over 6 days of weak winds and various convective boundary layers (9–11 March and 1–3 July 2004), and included  $\text{SF}_6$  releases at ground level monitored by both surface and airborne measure-



**Fig. 6.** Instruments to measure SF<sub>6</sub> dispersion: (a) The laboratory van equipped with a telescopic 10 m mast. SF<sub>6</sub> is released at 2 m 50 of height (seen behind the van). (b) Ground sampling with a drop by drop system. (c) Aircraft rack including 30 gas syringes

ments (Lac et al. 2008, this issue). The SF<sub>6</sub> was released at ground level during the period between 1 h and 3 h, in a suburban area (Fig. 6a). Sampling took place at ground-level (20 cm) and at altitudes of 100 m and 200 m aboard the Piper-Aztec, at distances between 280 m and 5000 m from the release point. At ground-level, samples were taken from the road edges and spaced from 100 m to 200 m (Fig. 6b). The sampling system for airborne measurements consisted of a rack including 30 gas syringes (Fig. 6c). Samples were later analyzed by gas chromatography in the IRSN laboratory van (Fig. 6a). The van was also equipped with an ultrasonic anemometer on a 10 m telescopic mast, allowing measurement of the mean and fluctuating wind components, and hence turbulence intensities and fluxes (heat and horizontal momentum). The van was located at the SF<sub>6</sub> release location.

#### 4. First results

In this section are summarized the first scientific results obtained from CAPITOUL, most of them being detailed in specific papers in this special issue. The reader is invited to refer to these papers for a more complete presentation of the scientific results he/she is interested in.

##### 4.1 Intra-annual variability of the surface energy balance (SEB)

The measurements carried out in Toulouse confirm previous results performed in dense urban environments. For example, the large heat storage ( $\Delta Q_S$ ) on sunny days, makes it possible to maintain a positive sensitive  $Q_H$  heat flux during the night (BUBBLE – Rotach et al. 2005 – ESCOMPTE – Grimmond et al. 2005 – Mexico City – Oke et al. 1999). Certain aspects of the urban energy balance that are infrequently or not included in previous work were studied here. For example, the intra-annual variability of the fluxes and the simultaneous assessment of the anthropogenic heat flux from both field observations and energy consumption data.

Table 5 shows the seasonal variability of the SEB for Toulouse downtown, as measured from the tower (anthropogenic heat flux is derived from other measured quantities as explained hereafter). The most interesting thing about net radiation is wintertime: it is almost zero. The solar input is completely counterbalanced by the long-wave loss, caused by the heated surfaces. When comparing turbulent fluxes to the net radiation, as is usually done (e.g. Grimmond et al. 2005), one observes values of  $Q_H/Q^*$  larger than one for spring and autumn, and a mean-

**Table 5.** Seasonal variation of surface energy balance observed from beginning of March 2004 to end of February 2005 for the dense old core of Toulouse

SEB quantity	$Q^*$ $W m^{-2}$	$Q_F$ $W m^{-2}$	$Q_H$ $W m^{-2}$	$Q_E$ $W m^{-2}$	$Q_H/Q^*$	$Q_E/Q^*$	$Q_H/(Q^* + Q_F)$	$Q_E/(Q^* + Q_F)$
Spring	81	26	83	24	1.02	0.30	0.77	0.23
Summer	123	15	105	32	0.86	0.26	0.76	0.24
Autumn	33	42	59	16	1.78	0.49	0.78	0.22
Winter	-1	76	61	14	-119	-28	0.81	0.19

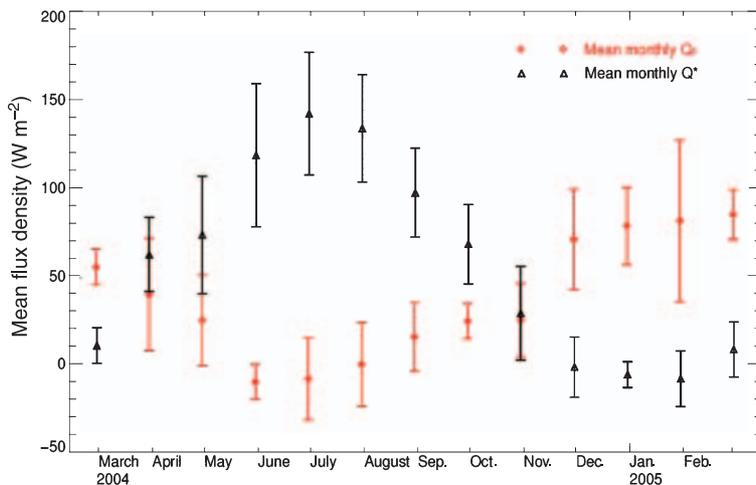
ingless value for winter. This is because another source of energy, namely  $Q_F$ , feeds the turbulent exchanges in addition to net radiation. Then, over Toulouse, the total energy is found to split as 78% into sensible heat flux and 22% into latent heat flux. This partitioning is almost constant during the whole year, with very few contrasts between the four seasons.

Over the city centre of Lodz, Poland, Offerle et al. (2006),  $Q_H$  varies between 50% and 60% of the available energy at a seasonal scale over two years. The difference could be attributed to the fact that Lodz site has more vegetated areas than Toulouse centre site (30% instead of 8%). Seasonal differences are also observed over Basel during BUBBLE (on two sites with 16% and 31% of vegetation): in winter, latent heat flux is just slightly smaller than the sensible heat flux, while in summer  $Q_H$  is twice as large as  $Q_E$  (Christen and Vogt 2004, their Fig. 10). This suggests that at the seasonal scale and for moderate climate cities, the energy partitioning variability is primarily dependant on vegetation evapotranspiration process (even in city centres), and only secondary on climatic conditions variability.

#### 4.2 Anthropogenic fluxes

The anthropogenic heat flux is first estimated from direct measurements of the SEB (at the central site). Instantaneous knowledge of the anthropogenic heat flux is not available, because only the residual, e.g.  $\Delta Q_S - Q_F$ , is known. However, Pigeon et al. 2007b show that over an extended period, the integral of storage becomes sufficiently small to be considered negligible. The monthly evolution of the anthropogenic heat flux deduced by this method is shown on Fig. 7. While the anthropogenic heat flux is around  $20 W m^{-2}$  during summertime, it increases in autumn and is a maximum in winter, reaching on average  $80 W m^{-2}$ , when space heating is important. In winter, anthropogenic heat becomes the main energy source of the urban canopy.

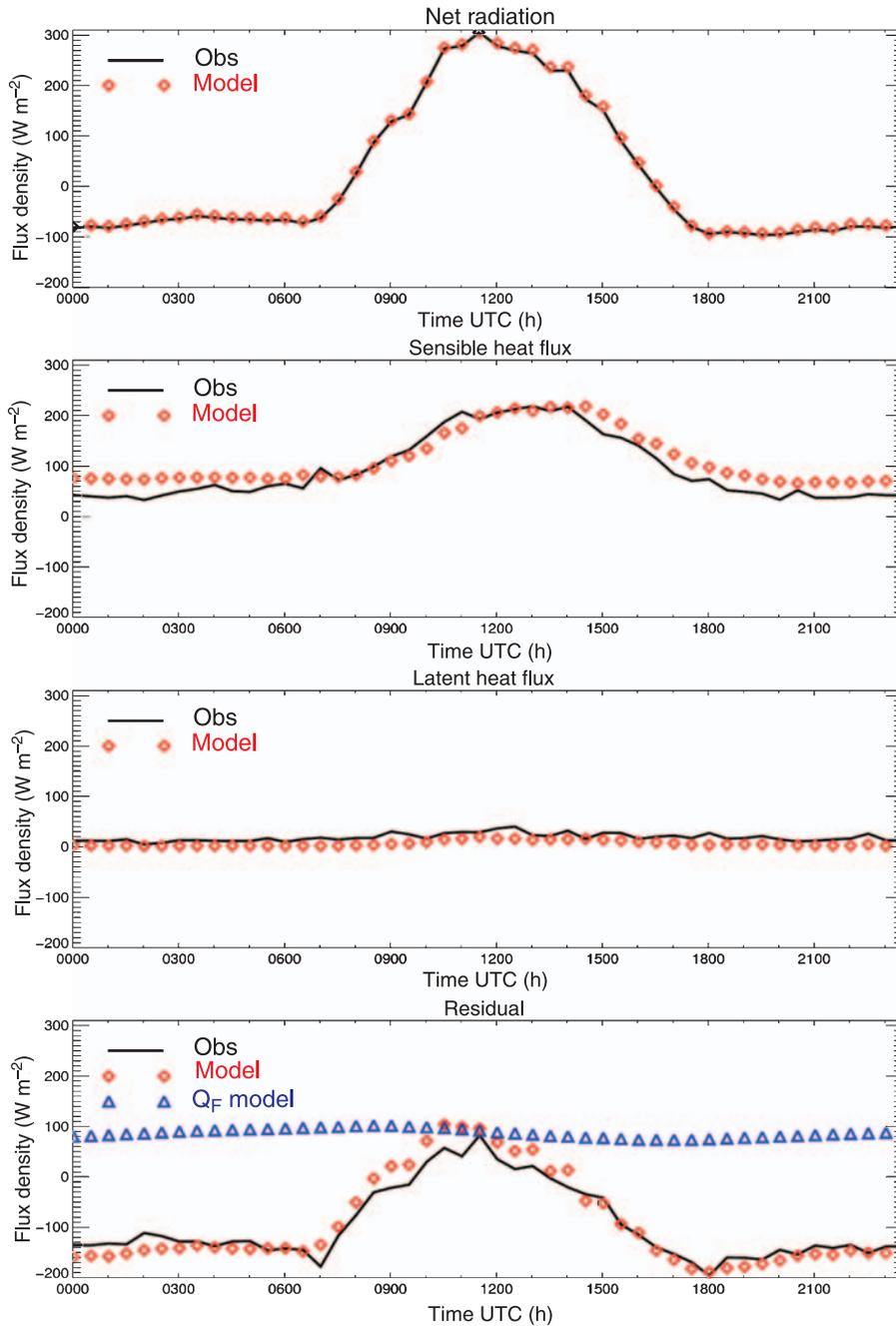
The estimation of  $Q_F$  from SEB residuals shows good agreement with the average energy consumption inventory (Pigeon et al. 2007b) for the area within a 500 m radius around the instrument tower (Table 6), and appears to reproduce the anticipated annual cycle of the anthropogenic flux.

**Fig. 7.** Annual cycle of net radiation (black) measured at the top of the central site tower, and of anthropogenic heat flux (red), estimated from the integrated residual method. Vertical bars indicate day-to-day variability

**Table 6.** Estimation of  $Q_F$  with a method based on surface energy balance observations and an inventory of energy consumption for the dense old core of Toulouse

	Winter (DJF)	Spring (MAM)	Summer (JJA)	Fall (SON)
SEB observations ( $W m^{-2}$ )	84	24	18	41
Inventory ( $W m^{-2}$ )	69	44	29	41

The energy balance measurements were used to validate the numerical Town Energy Balance (TEB) (Masson 2000; Masson et al. 2002; Lemonsu et al. 2004) urban scheme (Pigeon and 2008, this issue). The daily cycle of SEB terms computed by the model, averaged over for a 9 day cold wintertime period from 20 to 28 February 2005, are presented in Fig. 8 and compared with the observations from the tower. The diurnal cycle of the sensible heat flux is well reproduced,



**Fig. 8.** Comparison between TEB simulated and observed components of the surface energy balance. Mean diurnal cycle for the period 20–28 February 2005

with the correct intensity during the day. During the night, observations show a significant positive  $Q_H$  ( $50 \text{ W m}^{-2}$ ). This feature is specific to urban areas, and is due here to space heating. TEB reproduces the strong nocturnal sensible heat flux, although it is overestimated by  $25 \text{ W m}^{-2}$ . The simulation of the residual is correct ( $-95 \text{ W m}^{-2}$  observed,  $-92 \text{ W m}^{-2}$  modelled, see also bottom panel of Fig. 8) and the modelling of heating in TEB produces an anthropogenic heat flux as large as  $87 \text{ W m}^{-2}$ .

#### 4.3 Urban breeze circulation: observation and simulation

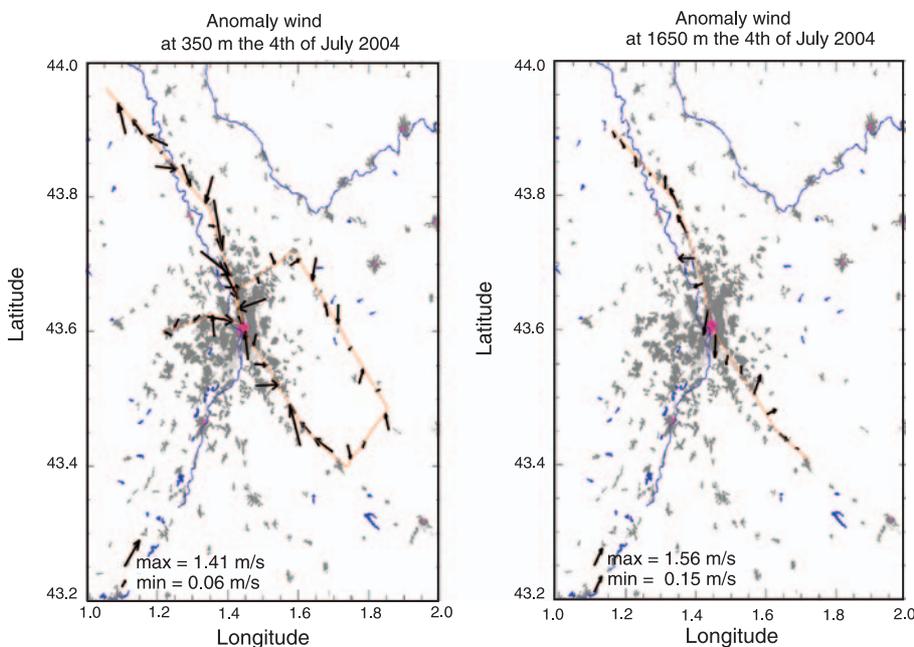
The urban breeze circulation is a concept presented by Oke (1987) by analogy with a sea or lake breeze: the thermal contrast related to differential warmth of two surfaces forms a horizontal pressure gradient that tends to produce air movement. At low level, the flow is directed from the colder towards the warmer surface, with a counter-flow forming aloft. In the case of a city, this leads to convergence at low-levels and divergence at the top of the boundary layer. This phenomenon has already been simulated (e.g. Lemonsu and Masson 2002). The airborne measurements deployed during CAPITOUL allow us to observe the characteristics of such a breeze experimentally, on the very hot summer day of July, 4th 2004 (Hidalgo et al. 2008a, this issue).

Figure 9 shows the anomaly of the wind field (in relation to the synoptic wind) measured during the afternoon by the instrumented aircraft. Convergence of a few metres per second forms at low levels (the flight altitude is 300 m), and a divergence of wind occurs at the top of the boundary layer. This breeze is created by a difference in the surface sensible heat flux of approximately  $300 \text{ W m}^{-2}$  between the city and the countryside in the afternoon, and extends horizontally to 2 to 3 times the mean size of the city.

This urban breeze episode was simulated with the MESONH model (Lafore et al. 1998) by Hidalgo et al. (2008b, this issue). Simulation reproduces the chronology and intensity of the events (UHI, diurnal heating and heat fluxes) well. The breeze is formed at the end of the morning in the model. The reproduced speeds are comparable with those of the observations. The mean vertical velocity above the city associated with this breeze reaches  $0.5 \text{ m s}^{-1}$ .

#### 4.4 Urban fog

In general previous work shows that fog is rarer in downtown environments. Radiation fog appears frequently in winter in the countryside, when surfaces and the overlying air cool during the night (Oke 1987). The fog is thus formed near the soil surface, and extends to the base of the nocturnal inversion, then thickens thereafter



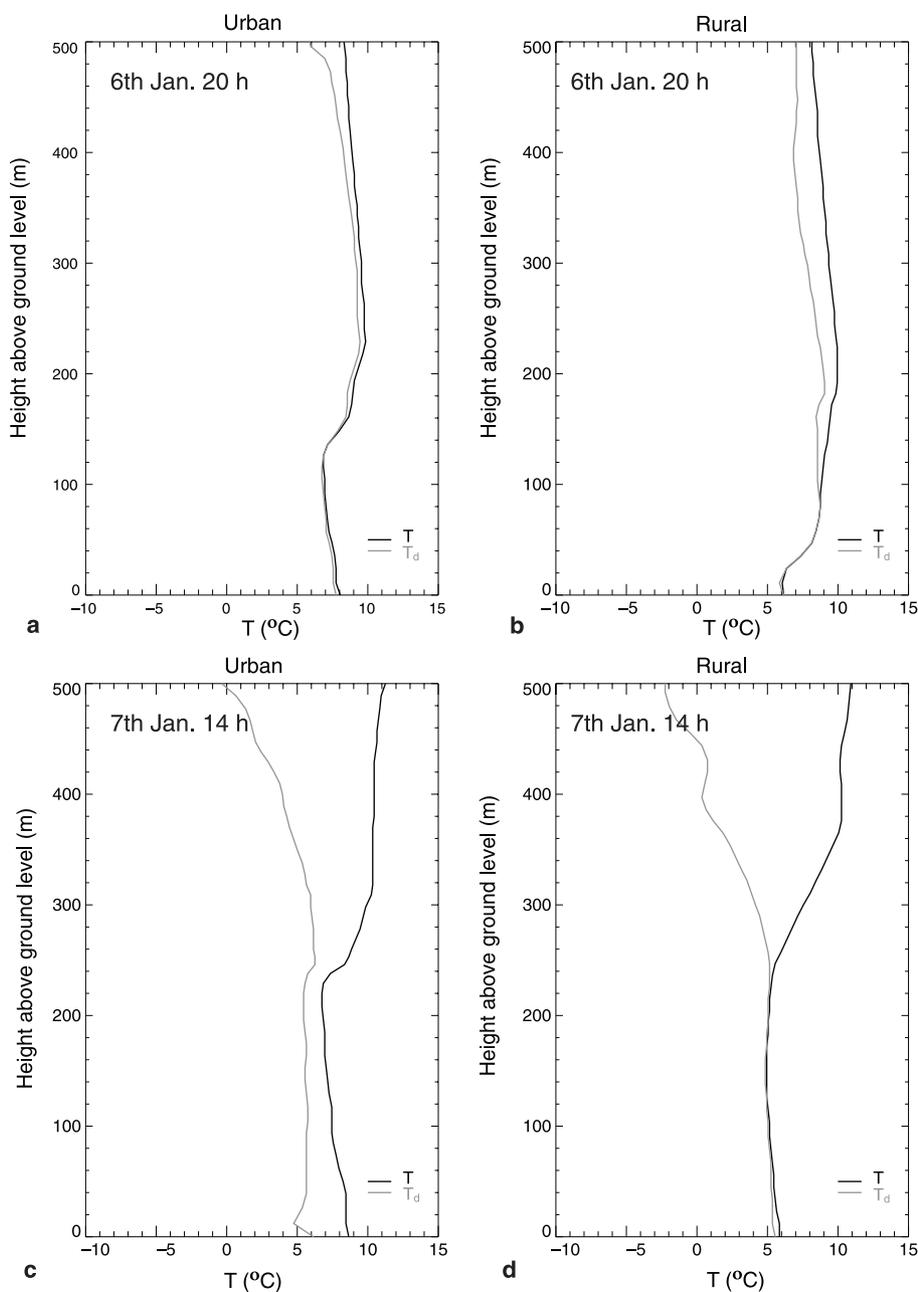
**Fig. 9.** Urban breeze during the afternoon of the 4th of July, 2004. Left: aircraft wind anomaly in the lower boundary layer (convergence). Right: aircraft wind anomaly in the entrainment zone (divergence)

by radiative cooling at the top of the fog. On the other hand, in cities the anthropogenic fluxes (winter heating) or nocturnal heat release (summertime  $\Delta Q_s$ ) produces upward sensible heat flux, forming a slightly convective layer typically 100 m–200 m deep instead of the classical nocturnal inversion.

Therefore one expects that downtown areas are characterized by fog which forms later and dissipates sooner. The CAPITOUL measurements confirm these facts, but also demonstrate, in several cases of fog, a counter-intuitive phenome-

non: when urban fog does manage to form, the fog in the downtown area is thicker (in height) than in the countryside.

Figure 10 shows the radiosoundings carried out on 6th January 2005 in the evening (20 UTC) and on the afternoon of the next day (14 UTC), in the downtown area (left panel) and in the countryside (right panel). It shows that in the countryside, a temperature inversion develops in the first few tens of metres, and that fog was formed there. It thickens in the classic manner during the night, to reach its maximum height the next



**Fig. 10.** Urban fog evolution: (a) urban and (b) rural radiosoundings on the evening of 6th of January, 2005. (c) urban and (d) rural radiosoundings in the afternoon of 7 January 2005. Black line is temperature, grey line is dew point temperature

day. On the other hand, the layer of fog in downtown immediately (from 20 UTC) reaches its maximum height, yielding a fog layer 3 times thicker than that in the countryside. The hypothesis advanced to explain this, which has to be detailed by modelling, is that when humidity is sufficient, fog is formed almost everywhere in the (slightly convective) mixed nocturnal urban boundary layer (of approximately 100 m in this case). Moreover, the high concentration of urban aerosol (mainly of black carbon, see below) in the city probably plays an important role in the development and especially the dissipation of the fog.

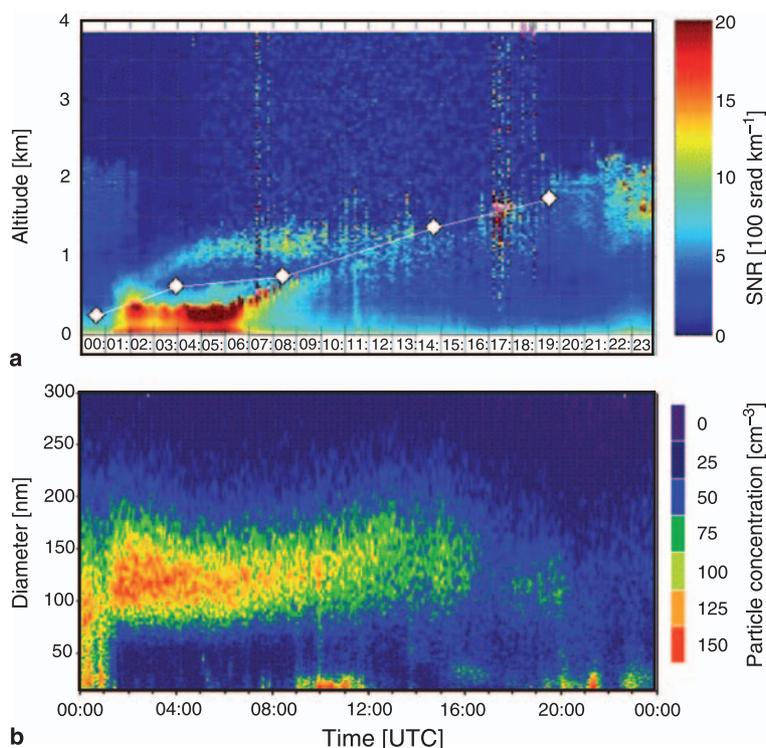
#### 4.5 New insights on urban aerosol

CAPITOUL confirms that urban aerosol is mainly composed of carbonaceous materials (BC plus OC) which is generally larger than 50% in the PM 2.5 fraction). Main influent sources are combustions: traffic and winter-time space heating. In winter, the Toulouse aerosol is enriched in ammonium nitrate due to the low ambient temperature which enhances the reaction between gas phase ammonia and nitric acid to form ammonium nitrate particles. In summer, the aerosol (crustal part plus carbonaceous part) is enriched

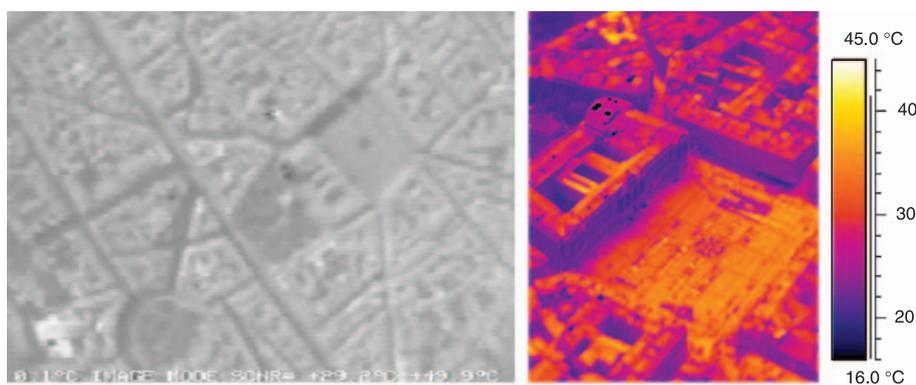
by sulphates and secondary organic aerosol due to the higher occurrence of photochemical activity. Trace element concentrations are low in Toulouse compared to the more polluted cities of Europe except for nickel and chromium (Calvo et al. 2008).

It is a current observation that the concentrations of aerosols downtown increase with the decrease of the boundary layer height (lid effect) during diurnal or seasonal cycles. The measurements of aerosol concentration compared with those of the boundary layer height from either radiosoundings or using the VAISALA ceilometer during CAPITOUL clearly show the existence of a relation between chemistry and atmospheric dynamics (Fig. 11).

CAPITOUL underlines the importance of the ratio BC/OC in the determination of the radiative impact of the aerosol. OC dominates in the accumulation mode by constituting most of the scattering component. BC, which is the most absorbing component, dominates in the ultra-fine mode and causes a sharp reduction in the value of the single scattering albedo (SSA). SSA therefore varies between 0.6 and 0.8 (diurnal average of 0.7) in this urban atmosphere, indicating an overall absorbing aerosol that is controlled by BC emissions. Additional observations allowed



**Fig. 11a.** Evolution of the boundary layer on the 27th June 2004, observed by the VAISALA modified ceilometer (color) and the radiosoundings (white diamonds). **(b)** Evolution of aerosol particles concentration per size class on the same day



**Fig. 12.** Examples of thermal images acquired over the Capitol square with the two TIR cameras: INFRAMETRICS M740, 2004 October 4, 11:11:51 UT (left) and FLIR SC2000, 2004 July 11, 13:47:23 UT (right)

us to estimate a daily direct radiative forcing for the period of June–July 2004 using a radiative transfer model (Mallet et al. 2005; Roger et al. 2006). Simulations show that aerosols significantly reduce the solar energy reaching the surface mainly by absorption of solar radiation in the atmosphere (Gomes et al. 2008, this issue). The obtained results indicate that the heating rate within the UBL is considerably enhanced with an average value of  $4.5 \text{ K day}^{-1}$  during daytime.

Particle concentrations in the  $0.3\text{--}2.0 \mu\text{m}$  size band observed at the top of the urban canopy layer follow the expected diurnal pattern in concentrations, with particle number increasing through the night to a peak during the early morning and decreasing through the afternoon period. However, comparison between two street canyons with different traffic flows, orientation and geometry shows considerable variation in particle number at the top of the urban canopy layer. In summer the concentrations of particles were highest during the day at the top of rue Alsace (due to the large volume of traffic) but at the top of the (narrow) Pomme street during the night (Salmond et al. 2006). This suggests that these (agglomeration mode) particles may have been stored within this narrow street canyon from earlier times and not efficiently vented into the atmosphere (this is confirmed by wavelet analysis of the coherent structures).

#### 4.6 Spatial, annual and diurnal heterogeneities of the surface temperature field

The aspects of the urban heat/cool island relate to average temperatures, however, spatial heterogeneity of urban surface temperatures is known to be large (Voogt and Oke 2003). Lagouarde

and Irvine (2008, this issue), analyze the directional variations in upwelling thermal infra-red radiation (anisotropy) and find a hot-spot effect of up to 5 K in the morning and 14 K in the afternoon (in winter), due to solar irradiation of the different surface facets. On winter nights, no azimuthal effect exists, as expected, but a zenithal dependence of 1 K is found between zenithal angles  $0^\circ$  and  $60^\circ$ . This dependency is due to the proportion of roof/wall seen by the sensor since the walls are warmer than the roofs, due to canyon trapping and possibly heating effects. Hand-held IR measurements show a vertical gradient of 3 K in wall temperatures at night.

These radiative heterogeneities of the urban surface, shown by the TIR data acquired during the campaign, will be modelled on a domain of approximately 1 km with the Gastellu-Etchegorry (2008, this issue) model.

#### 4.7 Evaluation of dispersion modelling

Despite the fact that  $\text{SF}_6$  releases were released in the same area and under almost the same meteorological conditions (convective conditions and same strength and direction of the wind), tracer measurements show the plume behaves differently from inhomogeneous turbulence (Lac et al. 2008, this issue). The dispersion appears to be mainly driven by the surface turbulent sensible heat flux that in turn is strongly sensitive to the time of day or to the transport induced by boundary layer clouds.

The dispersion modelling system PERLE, which is dedicated to operational emergency use in case of accidental release, has been evaluated with data from the  $\text{SF}_6$  CAPITOUL campaign. PERLE is based on the meso-scale

model MESO-NH, running at 2 km horizontal resolution, together with the Lagrangian stochastic model SPRAY. MESO-NH applied to the CAPITOUL SF<sub>6</sub> IOPs demonstrates an ability to supply realistic meteorological and turbulent fields to the dispersion model at this resolution. The urban surface scheme TEB strongly influences the structure of the ABL by reproducing the UHI. SPRAY then correctly predicts the general behaviour of the contaminant plume, the spatial distribution and location of concentration maxima in a coherent way using the meteorological and turbulent input fields. The main discrepancy between observation and measurement concerns the lateral spread of the plume, which is systematically underestimated under strongly unstable conditions. The diagnostic formulation of the standard deviation of the turbulent velocity components, which is based on the isotropic turbulence assumption, seems to be partially responsible for the lack of agreement. Different ways to improve performance are to be investigated.

## 5. Conclusions

The CAPITOUL campaign aimed to describe interactions between an urban surface, atmospheric circulations in the ABL (including the urban breeze circulation, fog and dispersion) and aerosols. The campaign took place over the city of Toulouse (in the southwest of France) for a whole year in order to detail seasonal variability of the physical and chemical processes under study.

The comprehensive nature of the observation campaign generated preliminary results concerning a wide range of urban climate questions. CAPITOUL confirms some results from previous studies. Examples are the importance of sensible heat storage in the urban surface energy budget and the large quantity of BC observed during diurnal pollution peaks. CAPITOUL also improved knowledge of several UBL processes and phenomena:

- A method to assess the anthropogenic heat flux using standard SEB measurements was developed (Pigeon et al. 2007b), and tested against heat inventories. Even for a city within a maritime temperate climate such as Toulouse,

wintertime space heating produces a large anthropogenic heat flux, which becomes the main energy input of the canopy in winter. The modelling of the anthropogenic heat flux by TEB has also been validated (Pigeon et al. 2008).

- An urban breeze circulation was observed on a warm summer day (Hidalgo et al. 2008a). While the city air is colder than that of the countryside in the morning, the sensible heat flux becomes larger during the afternoon ( $300 \text{ W m}^{-2}$  in the city, almost zero in the countryside), leading to the urban breeze circulation. Aircraft measurements show that an urban breeze starts in early afternoon, with convergence at low levels (with convergent winds between  $1$  and  $2 \text{ m s}^{-1}$ ), and divergence in the upper BL and the entrainment zone. This episode has been successfully simulated by Hidalgo et al. (2008b).
- Urban fog observations were puzzling. Urban fog develops later than in the countryside and dissipates sooner, as expected, but when present the layer is deeper over the city. An hypothesis to explain this is that in contrast to the stable nocturnal in the rural surroundings, over the city the BL is mixed through a depth of more than 100 m due to urban warmth and mixes the fog through the whole layer.
- An increase of the relative abundance of black carbon in the ultra-fine mode causes a decrease of the single scattering albedo of aerosols from 0.9 to 0.5, which can lead to a diurnal average heating value of  $4.5 \text{ K day}^{-1}$  in the UBL (Calvo et al. 2008; Gomes et al. 2008). There was a strong link between the UBL height and aerosol concentration. Wavelet analysis of turbulent aerosol measurements showed that both the shape of the canyon and season influence aerosol venting out of (or into) canyons. This strong seasonal variability was also observed in the chemical speciation of the aerosol, throwing into relief the influence of various dominant sources (Calvo et al. 2008).
- Previous findings of the variability of urban surface temperature and thermal anisotropy were confirmed during daytime. The first observations of nocturnal thermal anisotropy were conducted (Lagouarde and Irvine 2008). No azimuthal anisotropy was found at night, but there is a zenithal dependence. This can be

linked to the fraction of roofs viewed and to the vertical gradient of wall surface temperatures.

- In-situ and aircraft SF<sub>6</sub> tracer measurements in and over a suburban area show the plume to behave differently relative to inhomogeneous thermally-driven turbulence (Lac et al. 2008). The data were used to validate a coupled meteorology-dispersion model used in emergency response cases.

Data from the CAPITOUL campaign are available to the scientific community on the campaign web site (<http://medias.cnrs.fr/capitoul>). Hence any interested scientist can use this unique coupled energetics/dynamics/aerosols dataset in order to improve knowledge of urban climate.

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### References

- Allwine JK, Shinn JH, Streit GE, Clawson KL, Brown M (2002) Overview of URBAN 2000. *Bull Am Meteorol Soc* 83: 521–36
- Allwine KJ, Leach MJ, Stockham LW, Shinn JS, Hosker RP, Bowers JF, Pace JC (2004) Overview of joint urban 2003 – An atmospheric dispersion study in Oklahoma City, Planning, Nowcasting, and Forecasting in the Urban Zone Symposium, 84th AMS Annual Meeting, Seattle WA, USA
- Bastin S, Drobinski P (2005) Temperature and wind oscillations along a gentle slope during sea-breeze events. *Bound Layer Meteorol* 114: 573–94
- Briottet X, Lachéradé S, Pallotta S, Miesch C, Tanguy B, Le Men H (2006) Acquisition and analysis of a spectral and

- bidirectional database of urban materials over Toulouse (France), SPIE Defense and Security Symposium, Targets and Backgrounds XII: Characterization and Representation Conference – SPIE 6239-29, 17–21 April 2006, Orlando (Kissimmee), Florida, USA
- Cachier H, Aulagnier F, Sarda R, Gautier F, Masclet P, Besombes J-L, Marchand N, Despiou S, Croci D, Mallet M, Laj P, Marinoni A, Deveau P-A, Roger J-C, Putaud J-P, Van Dingenen R, Dell'Acqua A, Viidanoja J, Martins-Dos Santos S, Lioussé C, Cousin F, Rosset R (2005) Aerosol studies during the ESCOMPTE Experiment: an overview. *Atmos Res* 74(1): 547–63
- Calvo AI, Pont V, Lioussé C, Dupré B, Mariscal A, Zouiten C, Gardrat E, Castera P, Lacaux CG, Castro A, Fraile R (2008) Chemical composition of urban aerosols in Toulouse, France during CAPITOUL experiment. *Meteorol Atmos Phys* 102: 307–23
- Christen A, Vogt R (2004) Energy and radiation balance of a central European city. *Int J Climatol* 24: 1395–421
- Churnside JH (1992) Wave propagation in random media (scintillation). *Congress Optical Remote Sensing*. Seattle WA, USA, 1993, pp. 235–47 [Note(s): XII, 487 p.] (24 ref.), ISBN 0-8194-1062-4
- Cousin F, Lioussé C, Cachier H, Bessagnet B, Guillaume B, Rosset R (2005) Aerosol modelling and validation during ESCOMPTE 2001. *Atmos Environ* 39: 1539–50
- Cros B, Durand P, Prejafon E, Kottmeier C, Perros PE, Peuch V-H, Ponche J-L, Robin D, Saïd F, Toupance G, Worthan H (2004) the ESCOMPTE Program: an overview. *Atmos Res* 69(3–4): 241–79
- De Rosnay P, Jean-Christophe C, Yann K, Jean-Pierre W, Francois L, Maria JE, Munoz SJ, Kauzar S, Joel B, Gilles B, Laurent C, Guy C, Gerard D, Roger D, Nour EDF, Francis F, Joost H, Alain K, Francois L, David S, Philippe W, SMOSREX (2006) A long term field campaign experiment for soil moisture and land surface processes remote sensing. *Remote Sens Environ* 102(3–4): 377–89
- Gastellu-Etchegorry JP (2008) 3D modeling of satellite spectral images, radiation budget and energy budget of urban landscapes. *Meteorol Atmos Phys* 102: 187–207
- Gomes L, Mallet M, Roger JC, Dubuisson P (2008) Effects of the physical and optical properties of urban aerosols measured during the CAPITOUL summer campaign on the local direct radiative forcing. *Meteorol Atmos Phys* 102: 289–306
- Grimmond CSB, Salmond JA, Oke TR, Offerle B, Lemonsu A (2005) Flux and turbulence measurements at a densely built-up site in Marseille: heat, mass (water, carbon dioxide) and momentum. *JGR-Atmospheres*, 109, D24, D24101, 19 pp; DOI: 10.1029/2004JD004936
- Hidalgo J, Pigeon G, Masson V (2008a) Urban-breeze circulation during the CAPITOUL experiment: observational data analysis approach. *Meteorol Atmos Phys* 102: 223–41
- Hidalgo J, Masson V, Pigeon G (2008b) Urban-breeze circulation during the CAPITOUL experiment: numerical simulations. *Meteorol Atmos Phys* 102: 243–62
- Kanda M, Moriwaki R, Roth M, Oke TR (2002) Area-averaged sensible heat flux and a new method to determine

- zero-plane displacement over an urban surface using scintillometry. *Bound Layer Meteorol* 105: 177–93
- Klemm O (1995) Transport and distribution of air pollutants in Athens (Greece), Aircraft measurements during MEDCAPHOT-TRACE. In: Moussiopoulos N et al. (eds) *Air pollution III*, vol. 3: Urban Pollution, Computational Mechanics Publication, pp. 161–68. Southampton
- Lac C, Bonnardot F, Camail C, Connan O, Maro D, Hebert D, Rozet M, Pergaud J (2008) Evaluation of a mesoscale dispersion modelling tool during the CAPITOUL experiment. *Meteorol Atmos Phys* 102: 263–87
- Lachéradé S, Miesch C, Briottet X, Le Men H (2005) Spectral variability and bidirectional reflectance behaviour of urban materials at a 20 cm spatial resolution in the visible and near-infrared wavelength. A case study over Toulouse (France); *IJRS Lett* 26(17): 3859–66
- Lachéradé S, Miesch C, Boldo D, Briottet X, Valorge C, Le Men H (2008) ICARE: a physically-based model to correct atmospheric and geometric effects from high spatial and spectral remote sensing images over 3D urban areas. *Meteorol Atmos Phys* 102: 209–22
- Lafore J-P, Stein J, Asencio N, Bougeault P, Ducrocq V, Duron J, Fisher C, Hereil P, Mascart P, Masson V, Pinty J-P, Redelsperger J-L, Richard E, Vila-Guerau de Arellano J (1998) The Méso-NH atmospheric simulation system. Part I: Adiabatic formulation and control simulation. *Ann Geophys* 16: 90–109
- Lagouarde J-P, Irvine M (2008) Directional anisotropy in thermal infrared measurements over Toulouse city centre during the CAPITOUL measurement campaigns: first results. *Meteorol Atmos Phys* 102: 173–85
- Lagouarde J-P, Moreau P, Irvine M, Bonnefond J-M, Voogt J, Solice F (2004) Airborne experimental measurements of the angular variation in surface temperature over urban areas: case study of Marseille (France). *Remote Sens Environ* 37(5): 2508–17
- Lagouarde J-P, Irvine M, Bonnefond J-M, Grimmond CSB, Long N, Oke TR, Salmond JA, Offerle B (2006) Monitoring the sensible heat flux over urban areas using large aperture scintillometry: case study of Marseille city during the ESCOMPTE experiment. *Bound Layer Meteorol* 118(3): 449–76
- Lemonsu A, Masson V (2002) Simulation of a summer urban Breeze over Paris. *Bound Layer Meteorol* 104: 463–90
- Lemonsu A, Grimmond CSB, Masson V (2004) Simulation of the energy budget of an old mediterranean city core. *J Appl Meteor* 43: 312–27
- Lemonsu A, Bastin S, Masson V, Drobinski P (2006a) Stratification of the urban boundary layer of marseille under sea-breeze condition: joint analysis of doppler lidar and numerical simulations. *Bound Layer Meteorol* 118: 477–501
- Lemonsu A, Masson V, Pigeon G, Moppert C (2006b) Sea-town interactions over marseille: 3D urban boundary Layer and thermodynamic fields near the surface. *Theor Appl Climatol* 84(1–3): 171–8
- Lioussé C, Michel C, Bessagnet B, Cachier H, Rosset R (2004) 0D-Modelling of carbonaceous aerosols over greater Paris focusing on the organic particle formation. *J Atmos Chem* 51: 207–21
- Mallet M, Pont V, Lioussé C (2005) Modelling of strong heterogeneities in aerosol single scattering albedos over a polluted region. *Geophys Res Lett* 32: L09807
- Mallet M, Pont V, Lioussé C, Roger JC, Dubuisson P (2006) Simulation of aerosol radiative properties with the ORISAM-RAD model during a pollution event (ESCOMPTE 2001). *Atmos Environ* 40(40): 7696–705; DOI: 10.1016/j.atmosenv.2006.08.031
- Massera S (2005) Exploitation d'une base de données urbaines en vue d'extraire des paramètres utiles aux modèles météorologiques. Technical report, in french, Météo France, available on request from the authors
- Masson V (2000) A physically-based scheme for the urban energy budget in atmospheric models. *Bound Layer Meteorol* 94: 357–97
- Masson V (2006) Urban surface modelling and the meso-scale impact of cities. *Theor Appl Climatol* 84: 35–45
- Masson V, Grimmond CSB, Oke TR (2002) Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. *J Appl Meteor* 41: 1011–26
- Mestayer P, Durand P, Augustin P, Bastin S, Bonnefond J-M, Bénech B, Campistron B, Coppalle A, Delbarre H, Dousset B, Drobinski Ph, Druilhet A, Fréjafon E, Grimmond S, Groleau D, Irvine M, Kergomard C, Kermadi S, Lagouarde J-P, Lemonsu A, Lohou F, Long N, Masson V, Moppert C, Noilhan J, Offerle B, Oke T, Pigeon G, Puygrenier V, Roberts S, Rosant J-M, Saïd F, Salmond J, Talbaut M, Voogt J (2005) The urban boundary layer field experiment over marseille UBL/CLU-escomppte: experimental set-up and first results. *Bound Layer Meteorol* 114: 315–65
- Menut L, Vautard R, Flamant C, Abonnel C, Beekmann M, Chazette P, Flamant PH, Gombert D, Guédalia D, Kley D, Levebvre M-P, Lossec B, Martin D, Mégie G, Sicard M, Perros P, Toupance G (2000) Measurement and modelling of atmospheric pollution over the Paris area: The ESQUIF Project. *Ann Geophys* 18: 1467–81
- Offerle B, Grimmond CSB, Fortuniak K, Klysik K, Oke TR (2006) Temporal variations in heat fluxes over a central European city centre. *Theor Appl Climatol* 84: 103–15
- Oke TR (1987) *Boundary layer climates*, 2nd edn. Methuen, London, 435 pp
- Oke TR (1988) The urban energy balance. *Prog Phys Geog* 12: 471–508
- Oke TR, Spronken-Smith RA, Jauregi E, Grimmond CSB (1999) The energy balance of central Mexico City during the dry season. *Atmos Environ* 33: 3919–30
- Pigeon G, Lemonsu A, Barrié J, Durand P, Masson V (2006) Urban surface network in a coastal city: network optimization using numerical simulations and analyses of urban thermodynamic island. *Bound Layer Meteorol* 120: 315–51
- Pigeon G, Lemonsu A, Grimmond C, Durand P, Thouron O, Masson V (2007a) Divergence of turbulent fluxes in the surface layer: case of a coastal city. *Bound Layer Meteorol* 124: 269–90; DOI: 10.1007/s10546-007-9160-2

- Pigeon G, Legain D, Durand P, Masson V (2007b) Anthropogenic heat release in an old European city (Toulouse, France). *Int J Climatol* 27(14): 1969–81
- Pigeon G, Moscicki MA, Voogt JA, Masson V (2008) Simulation of fall and winter surface energy balance over a dense urban area using the TEB scheme. *Meteorol Atmos Phys* 102: 159–71
- Poutier L, Briottet X, Serrot G, Miesch C, Coret L, Malaplate A, Lemaître F, Dedieu G, Demarez V, Kerr Y, Marty G, Lavenu F, Calvet JC, Fritz N, Stoll MP, Nerry F, Barillot P (2002) PIRRENE: a multidisciplinary research program about field radiometry. *Int Symp OPTRO' 2002-AAAF*, Paris, France, January 2002
- Roger JC, Mallet M, Dubuisson P, Cachier H, Vermote E, Dubovik O, Despiou S (2006) A synergetic approach for estimating the local direct aerosol forcing during the ESCOMPTE campaign. *J Geophys Res* 111: D13208; DOI: 10.1029/2005JD006361
- Rotach MW, Vogt R, Bernhofer D, Batchvarova E, Christen A, Clappier A, Feddersen B, Gryning S-E, Martucci G, Mayer H, Mitev V, Oke TR, Parlow E, Richner H, Roth M, Roulet Y-A, Ruffieux D, Salmond J-A, Schatzmann M, Voogt JA (2005) BUBBLE – an Urban Boundary Layer Meteorology Project. *Theor Appl Climatol* 81: 231–61; DOI: 10.1007/s00704-004-0117-9
- Roth M, Salmond JA, Satyanarayana ANV (2006) Methodological considerations regarding the measurement of turbulent fluxes in the urban roughness sublayer: the role of scintillometry. *Bound Layer Meteorol* 121: 351–75
- Salmond J, Pigeon G, Legain D, Masson V (2006) Vertical transport of pollutants at night in Toulouse, France, 6th International Conference on Urban Climate, Göteborg, Sweden
- Sarrat C, Lemonsu A, Masson V, Guédalia G (2006) Impact of urban heat island on regional atmospheric pollution. *Atmos Environ* 40: 1743–58
- Steyn DG (2003) Scaling the vertical structure of sea breezes revisited. *Bound Layer Meteorol* 107: 177–88
- Voogt JA, Grimmond CSB (2000) Modeling surface sensible heat flux using surface radiative temperatures in a simple urban area. *J Appl Meteor* 39(10): 1679–99
- Voogt JA, Oke TR (1997) Complete urban surface temperature. *J Appl Meteor* 36: 1117–32
- Voogt JA, Oke TR (1998) Effects of urban surface geometry on remotely-sensed surface temperatures. *Int J Remote Sens* 19: 895–920
- Voogt JA, Oke TR (2003) Thermal remote sensing of urban climates. *Remote Sens Environ* 86: 370–84
- Willis GE, Deardorff JW (1976) A laboratory model of diffusion into the convective planetary boundary layer. *Quart J Roy Meteor Soc* 102: 427–45