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Titre:

UNE APPROCHE OBSERVATIONNEL, NUMERIQUE ET THEORIQUE A LA CIRCULATION DE BRISE URBAINE DIURNE POUR LES VILLES CONTINENTALES

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Introduction

D'un point de vue social, économique et météorologique, l'environnement urbain est un système complexe qui mérite, de nos jours, l'attention d'une communauté scientifique multidisciplinaire.

L'expansion urbaine comme tendance démographique dominante

La fraction de la population mondiale vivant dans les zones urbaines n'a pas cessé d'augmenter au vingtième siècle, de telle sorte que des économistes tels que L. R. Brown définissent l'urbanisation comme l'une des tendances démographiques contemporaines dominantes (Brown, 2001).

La population urbaine s'accroît trois fois plus rapidement que la population rurale (Nilsson *et al.*, 1999). Vers 2007, la population humaine a atteint un seuil critique, et à partir de cette date plus de la moitié de la population du monde vit dans des environnements urbains, faisant de nous, pour la première fois, une espèce urbaine (Brown, 2001). L'UNEP (Programme des Nations Unies pour l'Environnement) s'attend à une croissance de la population urbaine de 2% par an jusqu'en 2015. Il a été estimé que 60% de la population du monde résidera dans des zones urbaines d'ici à 2025 (Platt, 1994a).

L'urbanisation comme noeud d'échange économique

Les villes forment un réseau de centres concurrentiels qui constituent les points de référence physiques pour la mondialisation que nous connaissons aujourd'hui. Les zones urbaines tirent la croissance économique mondiale et, en même temps, constituent d'un point de vue social et environnemental un système anthropogène des plus vulnérables (Sanchez-Rodriguez *et al.*, 2004).

Les insuffisances dans le niveau de vie urbain comme le chômage, la faiblesse des services publics et les dégradations environnementales sont communes dans la plupart des villes. La vulnérabilité face à des événements météorologiques ou climatiques est l'un des problèmes majeurs (FCM-R22-2004). Les changements environnementaux globaux ont des conséquences potentiellement graves: influence sur la santé et le confort des habitants, coûts énergétiques (Fusaro, 2007), qualité de l'air et niveaux de visibilité (Wu *et al.*, 2006; Mikley *et al.*, 2004), disponibilité et qualité de l'eau, services écologiques, loisirs, et qualité de la vie générale. Une prévision exacte des caractéristiques du climat urbain est d'une importance première pour réduire les pertes économiques et garantir la sûreté des citadins.

Prévision à méso-échelle / Nowcasting: un outil essentiel

La météorologie urbaine est une approche spécialisée et interdisciplinaire pour étudier les interactions environnementales des communautés urbaines, en fournissant une réponse intégrée à ces demandes. Plusieurs conférences internationales sur le climat urbain ont été tenues depuis la fin des années 1960. Finalement en 2000, la communauté scientifique s'est organisée dans l'Association Internationale pour le Climat Urbain (IAUC). Cette structure regroupe des représentants de l'ensemble de la communauté du climat urbain et organise une conférence internationale tous les trois ans.

À mesure que la résolution des modèles de méso-échelle augmente, les techniques de prévision et de nowcasting appliquées à des domaines locaux/regionaux sont de plus en plus plus utilisées pour développer des protocoles améliorés de prise de décision. La prévision à méso-échelle est utilisée lors de dégagements toxiques dans l'atmosphère. Les actions sont plus utiles quand elles peuvent être mises en application et mises à jour rapidement, avec des temps de réponse de 15 minutes ou moins (Dabberdt *et al.*, 2000). Quand les modèles globaux prévoient des changements externes ou globaux importants, un run supplémentaire à l'échelle régionale peut être effectué pour atténuer les pertes dues à des événements climatiques extrêmes tels que tempêtes, vagues de chaleur, ou inondations.

En outre, la ville elle-même perturbe les conditions météorologiques locales et régionales, en créant des phénomènes spécifiques aux zones urbaines. La structure de la ville modifie la balance d'énergie de la surface (Oke, 1988) et la composition de l'atmosphère comparée aux terrains “naturels” l'environnant. La température montre le changement le plus évident. Les zones urbaines augmentent les conditions qui mènent à la concentration de chaleur créant les îlots urbains de chaleur, positifs et négatifs (Oke, 1982). L'impact sur la dynamique des flux (dû à l'hétérogénéité des surfaces, à la rugosité plus importante et aux gradients horizontaux de la température entre les environnements urbains et ruraux) est plus difficile à observer, mais est importante dans la gestion de la qualité de l'air, la conception de structures et le confort urbain (Willemsen, 2007).

Approfondir la compréhension de la dynamique des vents urbains

L'étude de l'impact urbain sur la dynamique de la couche limite atmosphérique (ABL) a un intérêt particulier en raison à l'étendue des applications. La perturbation peut avoir un rôle important pendant des situations météorologiques extrêmes (le brouillard, tempêtes, précipitations...) (Sheperd, 2005). En fonction des conditions météorologiques et des lieux, l'atmosphère perd sa capacité à transporter, diluer, transformer et enlever des polluants, causant de sérieux problèmes de santé. Les mouvements atmosphériques (vent et turbulence) pilotent la dispersion des polluants à diverses échelles. Le champ de vent est critique en ce qui concerne la dispersion horizontale, en déterminant à la fois la distance du transport sous le vent et la dilution de polluants dans la plume (Hunter, 1992). Une meilleure compréhension de la dynamique d'ABL permettra un meilleur aménagement de l'espace urbain, un confort accru pour les habitants et une meilleure prévention des risques.

Cette étude est concentrée sur la circulation locale créée en présence d'un îlot de chaleur urbain diurne, sous un ciel sans nuages et des vents régionaux très faibles, appelée circulation de brise urbaine (Oke, 1987). Différentes approches sont combinées pour avancer dans la connaissance de ce phénomène de méso-échelle, postulé théoriquement dans l'analogie avec la circulation de brise de mer, simulée avec des modèles numériques par quelques auteurs mais observée, seulement partiellement, avant cette étude (Wong and Dirks, 1978).

Dans le **chapitre 2**, une approche expérimentale de la brise urbaine est réalisée en utilisant des données expérimentales de la campagne de CAPITOUL (Toulouse, France 2004-2005). Pour évaluer les effets urbains de méso-échelle non mesurés, des simulations numériques de haute résolution sont utilisées pour completer et valider les données observées. Une approche numérique utilisant le modèle atmosphérique non-hydrostatique Meso-NH (Lafore *et al.*, 1998), couplé avec le schéma de surface urbain TEB (Masson, 2000) est réalisé dans le **chapitre 3**. Enfin une étude théorique des profils thermo-dynamiques de la température et du vent est effectuée dans le **chapitre 4** où un ensemble simple d'équations décrivant les dispositifs de brise urbaine est présenté.

Cette thèse est le résultat d'une collaboration entre le groupe TURBAU du CNRM/Météo-France (Toulouse, France) et le groupe de Physique de l'Atmosphére (FAO9) de l'Université de Vigo (Orense, Espagne). Ce travail a été développé au sein de l'équipe TURBAU pendant les deux premières années et le groupe FA09 pendant la dernière année. L'auteur a effectué la demande de Doctorat Européen à l'école doctorale de l'Université Paul Sabatier pour ce travail.

Introduction

From a social, economical and meteorological point of view, the urban environment is a complex system which deserves the attention of a multidisciplinary scientific community.

The urban expansion as a current dominant demographic trend

The fraction of world population living in urban zones has continued to increase in twentieth century, so much so that eco-economicists like L. R. Brown define the urbanization as one of the dominant demographic trends of our time (Brown, 2001).

The urban population is growing three times faster than rural population (Nilsson *et al.*, 1999). By 2007, human population reached a critical threshold, and from that point on more than half of world population will be living in urbanized environments making us, for the first time, an urban species (Brown, 2001). The UNEP (United Nations Environment Program) expects a growth of the urban population of 2% per year until 2015. It has been projected that 60% of the world's population will live in urban areas by 2025 (Platt, 1994a).

The urbanization as an economic hub

Cities establish the network of competitive centres that set the physical reference points for today's globalization. Urban areas are driving the world's economical growth and at the same time, from both a social and an environmental point of view, are one of the most vulnerable anthropogenic system (Sanchez-Rodriguez *et al.*, 2004).

Deficiencies in urban standard of living as unemployment, poor urban public services or environmental degradation are common in most of nowday's cities. Vulnerability faced with meteorological or climatological events is one of the major problems (FCM-R22-2004). Global environmental changes have potentially severe consequences in many ways: influencing the dweller health and comfort, energy costs (Fusaro, 2007), air quality and visibility levels (Mikley *at al.*, 2004; Wu *et al.*, 2006), water availability and quality, ecological services, recreation, and overall quality of life. An accurately forecasting of urban climate features is of primary importance to minimize economic looses and guarantee cityzens safety .

Mesoscale Forcasting/Nowcasting an essential tool

Urban meteorology is a specialized, interdisciplinary approach to study environmental interactions with urban communities providing an integrated response to these demands. As mesoscale model resolution increases, the forcasting and nowcasting techniques applied to local/regional areas are used to develop improved decision-making protocols. Mesoscale forecast is actually applied when a release of a toxic spill to the atmosphere occurs (e.g. in the Applied Meteorology Unit (AMU) in USA). Actions are most useful when they can be implemented and updated quickly, with response times of 15 min or less (Dabberdt *et al.*, 2000). When global models predicts important external or global weather changes, an extra run at the regional scale can be used to mitigate losses due to extreme weather events as storms, heat waves or floods.

Besides, the city itself perturbs the local and regional weather creating specific phenomena characteristic to urbanized zones. The structure of the city modifies the energy-balance of the surface (Oke, 1988) and the composition of the atmosphere compared to the surrounding 'natural' terrains. Temperature shows the most obvious alteration. Urban areas exacerbate conditions that lead to heat stress creating positive and negative *Urban Heat Islands* (Oke, 1982). The impact on the flow dynamics (due to the surface heterogeneity, larger roughness and horizontal temperature gradients between urban and rural environments) is more difficult to observe but is important in air quality management, structures design and urban comfort (Willemsen, 2007).

Going deeper in the urban wind dynamics comprehension.

The study of the urban impact on the ABL dynamics is of particular interest due to the large range of applications. The perturbation can have an important role during severe meteorological situations (fog, storms, strong precipitations...)(Sheperd, 2005). In function of weather conditions and location, the atmosphere loose it capacity to transport, dilute, transform and remove pollutants causing sever health problems. The atmospheric motion (wind and turbulence) pilots the dispersion of pollutants at many scales.

The wind field is critical with respect to horizontal dispersion determining both the distance of downwind transport and the pollutant dilution within the plume (Hunter, 1992). A better comprehension of the ABL dynamics will allow a better amenagement of the urban space, a higher comnfort for inhabitants and a better risk prevention.

This study is focused on the local circulation created in presence of a daytime *Urban Heat Island,* under cloudles skies when regional winds are very light, called *Urban-Breeze Circulation* (Oke, 1987). Different approaches are combined to advance in the knowledge of this mesoscale phenomenon postulated theorically in analogy with the sea-breeze circulation, simulated with numerical models by some authors but only partially observed before this study (Wong and Dirks, 1978).

Chapter 1

Convective boundary layer thermodynamics in urbanized environments

In this chapter the theoretical framework is presented. The atmospheric context (the Atmospheric Boundary Layer, ABL), the meteorological context (convective daytime situation), the geographical context (flat inland urbanised area), etc. are introduced accompanied by some references to key studies of each topic. It is not the objective of this chapter to do an extensive review of the ABL in general or of the Urban Boundary Layer (UBL) in particular.

1. The Atmospheric Boundary Layer

1.1. Definition and structure

The concept of a "*boundary layer"* attributed to Froude in 1870 was commonly used in fluid dynamics studies. In the field of aerodynamics the term was introduced later by Prandtl (1905) referred to the flow of a fluid of low viscosity close to a solid boundary. In the atmospheric context, the ***Atmospheric Boundary Layer (ABL)*** is the layer of the atmosphere (belonging to the troposphere) influenced directly by the roughness and energy balance of the surface (of obvious importance with respect to emissions, transport and human exposure).

The ABL extends to heights of approximately 100 m under stable conditions to 2500 m under convective conditions. It responds to surface forcing in a time-scale of an hour or less. In this layer physical quantities such as flow velocity, temperature, moisture etc., display rapid fluctuations (turbulence) and vertical mixing (Stull, 1997).

Figure 1.1 illustrates a typical daytime evolution of the idealized atmospheric boundary layer in high pressure conditions over land[1]. Studies conducted to describe the ABL diurnal cycle under unstable conditions were started in the seventies based on observational fields, laboratory models and numerical modeling simulations (Wyngaard and Coté, 1974; Willis and Deardorff, 1974; Andre *et al.*, 1978). The solar heating causes thermal plumes to rise, transporting moisture, heat and aerosols. The plumes rise and expand adiabatically until a thermodynamic equilibrium reached at the top of the atmospheric boundary layer. The moisture transferred by the thermal plumes forms convective clouds.

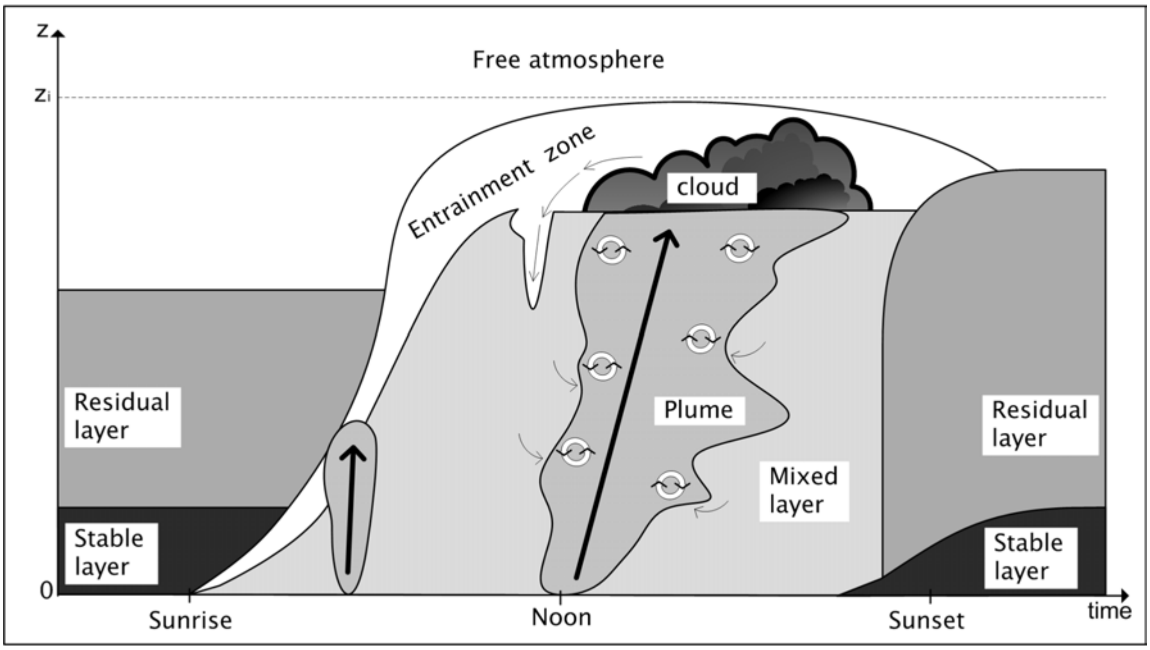

Fig.1.1: Vertical cross-section representing the daytime evolution of the idealized ABL.

Drier air from the free atmosphere penetrates down, replacing rising air parcels. The part of the troposphere between the highest thermal plume tops and deepest parts of the sinking free air is called the ***entrainment zone***. The top of the entrainment zone corresponds to the top of the ABL characterized by a capping inversion in which temperature actually increases with height (Crum, 1985). Due to the interfacial stability change, Kelvin-Helmholtz waves and internal gravity waves are generated (Stull, 1976).

The convective air motions generate intense turbulent mixing. This tends to generate a ***mixed layer***, the turbulent dry convection rapidly stirs the layer to near-neutral buoyancy and near-constant water vapour mixing ratio with potential temperature and humidity nearly constant with height. When buoyant turbulence generation dominates the mixed layer, it is called a ***convective boundary layer (CBL)*** that gradually erodes the stable layer above the ABL to reach its maximum depth by late afternoon. The lowest part of the ABL is

[1] This study is centred on the urban surface impact on ABL that is why development and influence over oceanic surfaces are not described.

called the ***surface layer***. In windy conditions, the surface layer is characterized by a strong wind shear caused by friction. The similitude theory of Monin-Obukhov is satisfied in this layer (Obukhov, 1946; Monin and Obukhov, 1954; Rotach, 1993), a complete study of the flux profiles in this layer presented by Bussinger (1971).

The boundary layer from sunset to sunrise is called the ***nocturnal boundary layer***. It is often characterized by a ***stable boundary layer (SBL)*** (typically only a few hundred meters deep), which forms when the solar heating ends and the radiative cooling and surface friction makes more stable the lowest part of the ABL. Above that, the remaining of the daytime CBL, ***the residual layer***, contains mixed layer air from the previous daytime period. Observational and theoretical studies conducted specifically to the nocturnal ABL features are numerous in the literature from 1930-1940 and it features are now well know (Brost and Wyngaard, 1978; Delage, 1974 or Estournel *et al.,* 1986). A good review about the subject could be found in Stull (1997).

Above the ABL is the ***free atmosphere*** where the wind is approximately geostrophic (parallel to the isobars). The free atmosphere is usually non turbulent, or only intermittently turbulent.

This is a idealized description of the diurnal cycle under weak large-scale winds, there are some situations in which mechanical effects dominate thermal effects in the boundary layer energy balance (i.e under strong large-scale winds) and this idealized diurnal evolution does not apply.

1.2. ABL features and its meteorological framework

The present study is focused on daytime ABL under anticyclonic summer situations where light large-scale winds and hight sunshine permits a mixed and well developed ABL. The meteorological situation has strong influence on the ABL properties but is possible to do a classification for some idealized standard cases.

1.2.1. ABL classification

The ABL structure can be complex, involving a diverse mixture of processes and space and time dependencies. The simplest cases are those with horizontally homogeneous and steady conditions, and are classified by stability.

Atmospheric stability can be defined qualitatively as a measure of the degree of vertical mixing in the atmosphere (Kaimal and Finningan, 1994). Atmospheres that are poorly mixed in the vertical direction are said to be ***stable***. Conditions of extreme stability may be associated with either elevated or ground-based inversions. Atmospheres that have significant vertical mixing are said to be ***unstable***. Those atmospheres of moderate vertical mixing are often said to tend toward **neutral stability**.

The spectrum of atmospheric stabilities cited before are directly related to the amount of **Turbulent Kinetic Energy** (TKE) in the atmosphere. This TKE is generated by two basic mechanisms: (1) **mechanical shear** caused by air flow over the earth's surface and (2) **buoyancy-induced vertical acceleration of air**. A good compilation of the existing studies analyzing the structure of the dominated shear-induced motions and the buoyancy-dominated motions was done by Khanna (1998). The first mechanism becomes more important in the near vicinity of the earth's surface, and is generally the dominant mechanism for stable and neutral stability conditions. Buoyancy-induced turbulence generally leads to the greatest amount of vertical mixing in the atmosphere and is associated with hot and sunny days.

However, the ABL involves a variety of features and processes in addition to shear and buoyancy. Other thermodynamic processes that affects the ABL are Coriolis force produced by planetary rotation, and factors such the formation of clouds and radiative heat transfer.

1.2.2. Convective ABL

The CBL can be divided into three parts (Figure 1.2), the ***surface layer*** (heights less than z_s, where temperature (Θ) and moisture (q) decrease and the wind component (u) increase rapidly with height), the ***mixed layer*** (heights z_s to z_{ML}) where (Θ, q, u and v) are nearly constant, and the ***entrainment layer*** (heights z_{ML} to z_i), where all four variables change rapidly with height from the mixed layer values to those of the atmosphere above. The inversion height z_i is drawn roughly halfway through the entrainment layer, where vertical gradients are a maximum. Above the interfacial layer, the stratification is that of the free atmosphere.

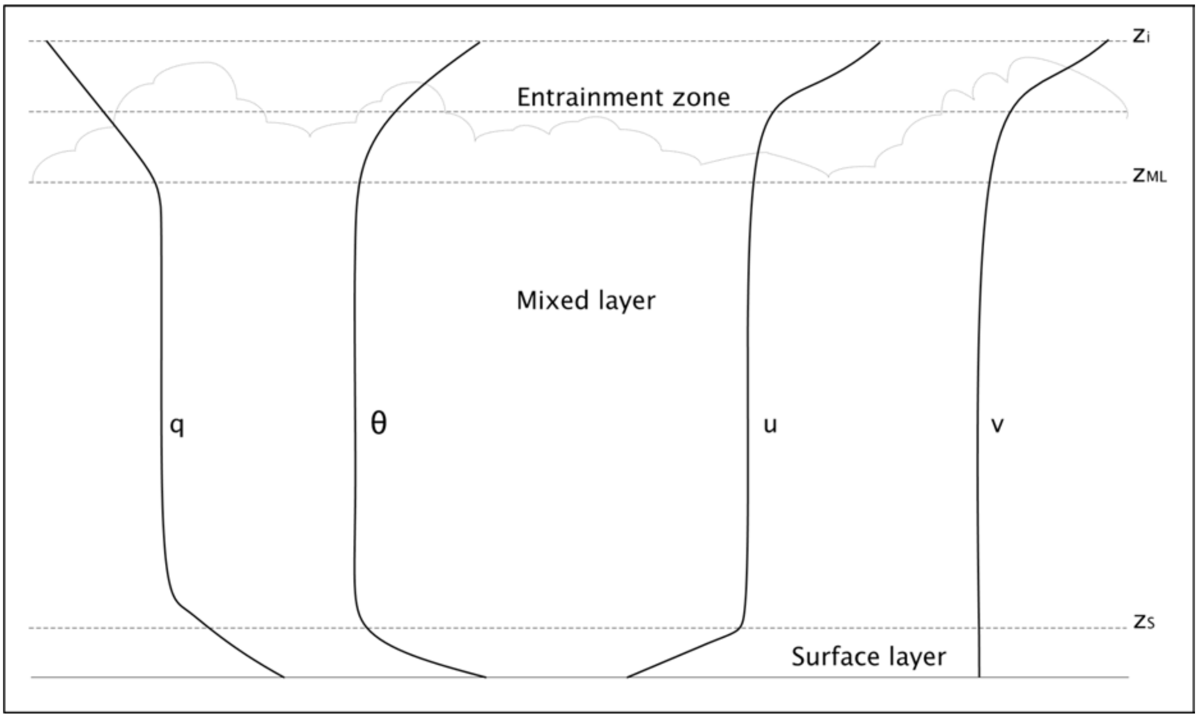

Fig. 1.2: Idealized profiles of horizontally averaged potential temperature (Θ), specific humidity q, and wind components u and v in the convective boundary layer. (adapted from LeMone 2003)

Momentum is also well mixed through most of the CBL (Lenschow, 1980). The momentum is determined by a balance between pressure gradient force $(-1/\rho_a)\nabla P$, the Coriolis force ($f\kappa \times \mathbf{V}$) (where f is the Coriolis parameter, κ the von Karman constant and **V** the wind vector) and the surface friction F_r (LeMone, 2003). At equilibrium:

$$f\kappa \times \mathbf{V} = (-1/\rho_a)\nabla P + F_r$$

On average, the wind speeds over land **V** are lowest during the night, when the stable nocturnal inversion decouples the surface from the wind overhead; and are largest during the day, when the momentum from above is mixed downward by the CBL (Garrat, 1992). The wind vector is paralel to the isobars above the CBL where friction is negligible. Within the CBL, the Coriolis force is reduced as a result of frictional slowing of the wind, and the air flows down the pressure gradient toward lower pressure. In the northen hemisphere CBL, the mixed-layer wind (*u*) flows in a direction 20-30 degrees to the left of the wind above the CBL. The rotation of the wind from the surface-layer direction to the free atmosphere is concentrated in the entrainment layer (Kim, 2003).

Vertical turbulent velocities tend to peak some way above the ground, with lower values near the ground and at the BL top. Horizontal turbulent velocities, however, are more uniform and there are not blocked for the presence of the ground. The typical velocity scale is linked to the ABL depth z_i and is of the order the **convective velocity scale w*** (Deardorff, 1970b) given by the equation:

$$w* = \left(\frac{\beta z_i H}{\rho_0 Cp} \right)^{1/3}$$; $\beta = g\Theta^{-1}$ is the buoyancy coefficient

A typical value for daytime CBL in mid-latitudes is about 1-3 m s^{-1} (Godowitch, 1986; Johnson, 1998).

The largest eddies extend throughout the depth of the CBL. The depth of the dry CBL is thus determined by the temperature of the upfrafts and the change of temperature with height in the environment (Wilczak, 1984). In summer in mid latitudes with clear skies rapid growth typicaly continues until the CBL reaches a depth of 1-2 km about 11.00 to 12.00 local time. With heating being continually added at the surface, a steady situation is impossible and the ABL grows slowly in a quasy-steady state for the next 4-5 hours with a slowly changing depth as the stable stratification above the boundary layer is eroded (Wilde *et al.*, 1985).

The top of the CBL is uneven typically higher where large-eddy motions are upward. On average, there are fewer thermals in the downwelling portions of the larger eddies, which are thus less turbulent than the upwelling regions. When the CBL grows deep enough for rising thermals to reach their condensation levels, clouds form. The evolution of cloud formation and the depth of the ABL affects the maximum surface temperature and the formation of showers.

1.2.3. Vertical fluxes in the CBL

The exchanges of energy between the surface (defined as the surface as well as all obstacles: low vegetation, trees, buildings…) and the atmosphere can be quantified using the concept of Surface Energy Balance (SEB) described in Oke (1987). Over land in clear-sky situations, energy echanges surface-atmosphere are governed by the diurnal cycle of solar radiation. For natural covers surface radiative imbalance is accounted combining the convective exchange to or from the atmosphere, either as sensible (Q_H) or latent heat (Q_E) and conduction to or from the underling soil (Q_G). In other words, the incoming radiation is an external forcing, while the sensible, latent and ground fluxes are the response, being the surface balance:

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

The sign convection is that positive fluxes indicate upward transport of the quantity (lose of heat from surface), otherwise they have negative sign.

The partitioning of the radiative surplus (when Q*>0) or deficit (when Q*<0) between the terms Q_H, Q_E and Q_G is governed by the nature of the surface and the relative ability of the atmosphere to transport heat. The last one is directly linked with the meteorological context.

The sensible (Q_H) and latent (Q_E) heat flux could be calculated as function of the temperature and moisture fluxes ($\overline{w'\theta'}$ (K m s^{-1}) , $\overline{w'q'}$ (g kg^{-1} m s^{-1})).

$$Q_H = \rho C_p \overline{w'\theta'} \quad (\mathrm{W\ m^{-2}})$$

$$Q_{LE} = \rho L_v \overline{w'q'} \quad (\mathrm{W\ m^{-2}})$$

In a CBL the mixed layer profiles of vertical fluxes of Θ_v, q and u are linear (Figure 1.3). The vertical q-flux depending on meteorological conditions can decrease or incrase with height. A decrease of Θ-flux with height to about -0.2 times the surface flux at z_i has been commonly observed (LeMone, 2003). In absence of horizontal temperature gradients the pressure gradient force is nearly constant with height. Wind components *(u)* and *(v)* are nearly constant (Figure 1.2) and hence is possible to derive (Stull, 1997; LeMone, 2003) that the profile of $\overline{u'w'}$ is nearly negatively linear (increasing from negative to zero values at z_i) (Figure 1.3).

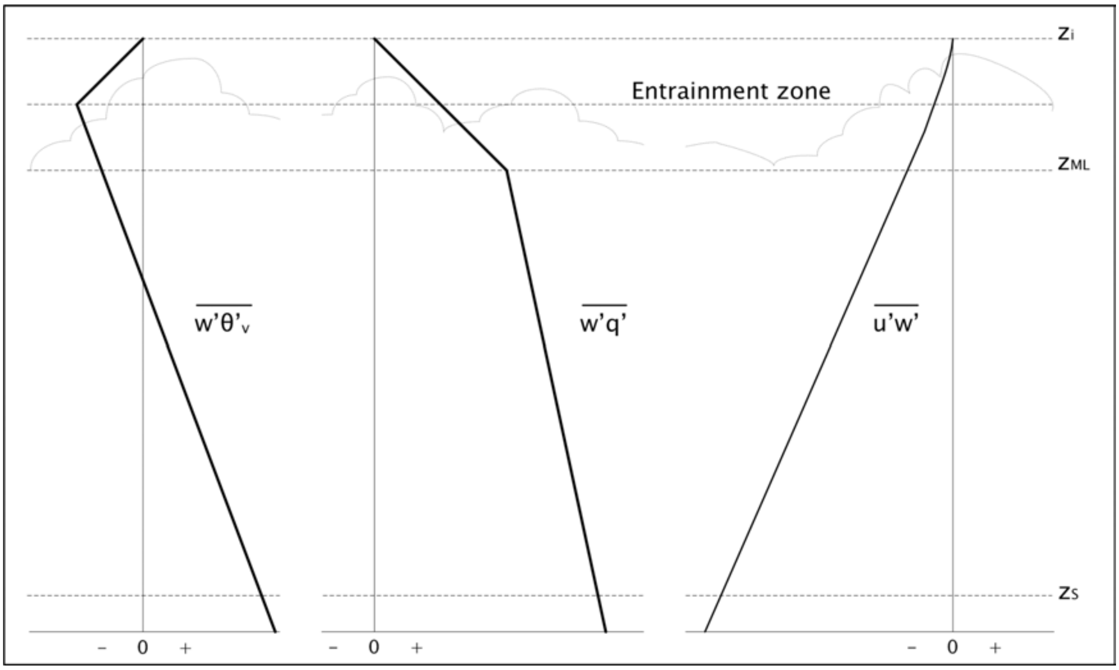

Fig. 1.3: Idealized vertical profiles of the vertical flux of virtual-potential temperature flux $\overline{w'\theta'}$ *, specific humidity* $\overline{w'q'}$ *,and the u-momentum flux* $\overline{u'w'}$ *(parallel to the mean surface-layer wind) (adapted from LeMone 2003).*

1.2.4. Air quality in CBL

Air pollutants are substances which, when present in the atmosphere under certain conditions, may be injurious to human, animal or microbial life. Two classes of factors determine the amount of pollution at a site (Oke, 1987) (I) the nature of emissions and (II) the state the atmosphere.

The first work on passive plumes in the CBL, done by Willis and Deardorf (1977, 1980) in the laboratory, showed that plume behavior is a function of release height. These results were confirmed by Lamb (1982) and from atmospheric dispersion experiments during the CONDORS field study (Kaimal *et al.,* 1986). Pollutants emitted from smoke stacks exhibit a characteristic ***looping*** as those portions of effluent emitted into warm thermals begin to rise and are dispersed rapidly (Figure 1.4). Vertical mixing decrease air pollution near the ground from nearby sources. However, convective conditions can lead high near-surface concentrations from releases from elevated or distant stacks because the rapid mixing can bring material down to the ground quickly before it has been much diluted, this process is called ***fumigation*** (Figure 1.4).

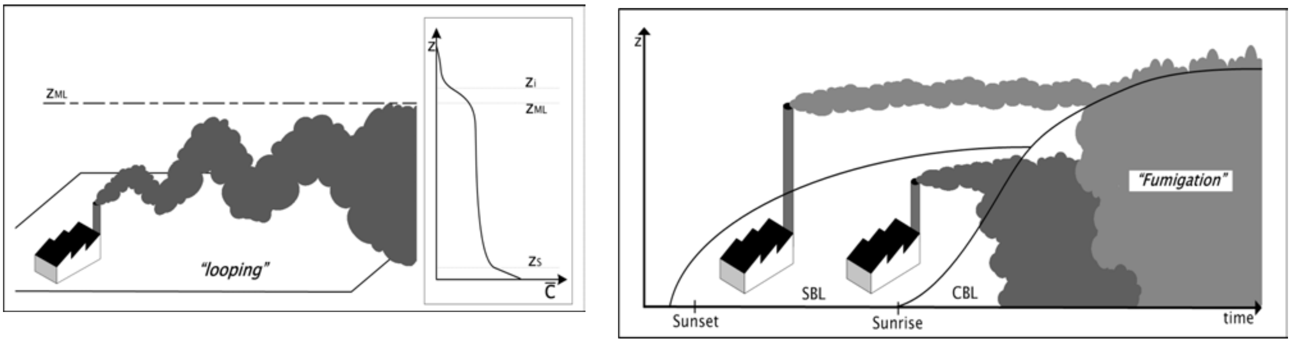

Fig. 1.4 Pollutants dispersion on CBL. Looping and Fumigation phenomenons (adapted from Stull 1997).

Explicit modelling is needed if one wants to look in detail at the processes that occur in street canyons and to predict canopy level climatology, or to couple detailed traffic emission models with meteorology, in which case knowledge of the vertical profiles of turbulence characteristics in the street canyons is required. Large-eddy simulations is a good tool to study the plume behaviour in the CBL where the large scale turbulent motions are calculated by solving explicitly the equation of motion on a numerical grid and the scales of motion smaller than grid size are parametrized. Large-eddy modelling has been first applied to CBL dispersion by Lamb (1982).

When only the overall effect of cities on the overlying ABL is in interest in the context of pollution dispersion at a regional scale, a non-explicit approach may be sufficient for the main parameters such as albedo, thermal admittance, roughness and moisture availability. In global and mesoscale numerical models, to represent the largest eddies in the CBL who pilots pollutants dispersion, a first-order gradient-diffusion approach to close the equations with (optionally) a non-local or counter-gradient (Andren 1990, Holtslag and Boville 1993, Hurley 1997) term for scalar fluxes are used. A recently developed alternative method to represent turbulence in the convective boundary layer is one that parameterises the vertical flux of a scalar as the sum of a gradient-diffusion term to represent the small-scale eddies and a mass-flux term to represent the large-scale convective eddies. Siebesma and Teixeira (2000) and Teixeira and Siebesma (2000) used this approach in the European Centre for Medium-Range Weather Forecasts (ECMWF) global model together with a profile-specified eddy-diffusivity closure, while Soares *et al.* (2004) used this approach, together with one-equation prognostic turbulence using the mixing length closure within the mesoNH model. Soares *et al.* (2004) treated both dry and moist convection in the Eddy-Diffusivity Mass-Flux parametrization scheme (EDMF) framework, and demonstrated that this approach has the potential to represent turbulence processes in dry and moist convection within a unified approach rather than as separately parametrised processes.

A recent study (Hurley, 2007) applies the EDMF approach but using a two-equation prognostic turbulence equation model within The Air Pollution Model (TAPM; Hurley 2005a, b), combined with the mass-flux model from Soares *et al*. (2004) to modelling mean and turbulence fields in the dry convective boundary layer.

1.3. ABL roles at the "global" and "local" scales

The ABL has an important influence in the behaviour of the atmosphere as a whole. Activities involving the representation of the atmosphere such as climate modelling and numerical weather prediction cannot succeed without the ABL being represented in some detail (Burk, 1989). The main influences on the atmosphere as a whole are as follows:

- Over level terrain, the drag between the atmosphere and the surface is the main mechanism by which the energy in the large-scale motion is dissipated. With small-scale orography the drag also occurs through pressure forces whose magnitude is influenced by the ABL turbulence (Bougeault, 2000).
- It buffers the transfer of heat and moisture between the surface and the atmosphere, in particular, the way surface solar heating is partitioned into sensible and latent heat fluxes.
- It is critical in determining the properties of air forming clouds and moist convection. It plays a central role in determining the occurrence of low-level clouds and consequential effects on radiation budgets (Siebesma, 1998).
- It tends to retain aerosols and pollutants from the surface, with the transfer of such polluted air to the free troposphere being limited mainly to moist convection and frontal motions which, though washout, leave the main atmospheric air freer of such material.

The ABL is of particular significance to human activities and natural processes occurring on the

Earth's surface. Prediction and understanding of the local environment requires an understanding of the ABL at the local scale. In particular the ABL is important for predicting a range of parameters such as: the surface wind and turbulence, daily maximum and minimum temperatures, visibility and fog and the dispersion of pollutants and other material.

1.4. Thermal circulations dynamics

Coherent structures tend to be particularly well defined where one type of phenomenon dominates the ABL dynamics (in the case of CBL with low winds, the flotability is the phenomenon who pilots the ABL dynamics). Structures contribute significantly to the overall dynamics of the flow. That is why they tend to determine the form of the velocity spectra, e.g. of the vertical and horizontal components. Structures also affect the statistics of extreme events, such as large gusts or high downbursts of pollution.

Coherent structures in the atmosphere need to be understood and described in order to deal more effectively with engineering and environmental problems. Examples are wind energy, wind loading on strucutres, aircraft operation, blowing of dust and snow, propagation of electromagnetic waves, wind shelter design and dispersion of pollution. Study of coherent structures is also helpful in interpreting statistical data (such as spectra, correlations and probability distributions) and can also be used for interpolation when data are not available or for extrapolation to more complex situations.

Atmospheric phenomena within the ABL are characterized by space (determined by their typical size or wavelength) and time (typical lifetime or period) scales. Local fluctuations of the circulation derived from differential heating induced by the diurnal cycle and surface heterogeneities belong to the meso-ß scale (10-100 km) with a typical lifetime of 5-8 hours (Oke, 1987).

Spatial inhomogeneity can originate two diferent effects:

- Advective effects: horizontal motions starts and air moves from one distinct surface type to a different one.
- Thermal circulation system: is the circulation of air induced by contrasting surface properties when regional winds are weak.

This last one is our study case, the juxtaposition of contrasting thermal environments resutls in the developement of horizontal pressure gradient forces, which is sufficient to overcome the retarding influence of friction will cause air motion across the boundary between surfaces.

Some examples are the ***Land and sea (lake) beezes***, land and water surfaces possess contrasting thermal responses because of their different properties and energy balance, and this is the driving force behind the land and sea (lake) breeze circulation system encountered near the ocean or lake shorelines. The sea-breeze is a well documented mesoscale flow. Studies directed to explore its properties and structure, its dynamics and its overall impact on the air quality of coastal cities from an experimental, numerical or theoretical point of view are numerous. Fisher (1960), Walsh (1974), Atkinson (1981), Rotunno (1983), Nakane (1986), Niino (1987), Finkele (1995), Feliks (1994), Lemonsu (2004c), Lemonsu *et al.* (2006a, 2006b), Augustin (2006) are only an example of the importance that adquired the field in last decades.

The ***Urban-breeze circulation***, can develop when regional winds are very light or calm. The horizontal temperature (and therefore pressure) gradient across the urban/rural boundary can be sufficient to induce low-level breeze from the country into the city. Urban-breeze circulation is the central topic of this study and is described in depth in point 3.

2. ABL specificities in urbanized environments

The ABL properties tends to respond to an area average of the surface properties. The accuracy on the description of the surface turbulent flow is a key issue because is critical to the overall ABL properties (Finnigan, 2003). The task of representing the surface is made more difficult by the presence of heterogeneity in the surface as when a city is present.

2.1 The urban boundary layer

2.1.1 Definition

The ***Urban Boundary Layer (UBL)*** is the portion of the ABL above the ***urban canopy*** (layer of air between the surface and the roofs level; Oke, 1987) whose climatic characteristics are modified by the presence of a city at the surface.

The UBL has received increased attention for characterising and understanding its structure and behaviour (e.g. Oke *et al.,* 1999; Grimmond and Oke 1999a,b). The urban surface morphology and structural characteristics perturbs the ABL and generates atmospheric phenomenons specifics to the urban environment with a characteristic scale going from the microscale to the mesoscale as: reduction of dewfall (Richards, 2004), reduction of radiation fog in within cities (Sachweh and Koepke, 1995; Sachweh and Koepke, 2004), night-time and daytime heat islands, cold islands, dry islands (described in point 2.2), leeward rainfall enhancement (Sheperd (2005) provides a concise review of recent (1990–present) studies related to how the urban environment affects precipitation), etc.

Comparing with the surrounding landscape the city possesses its own combination of radiative, thermal, moisture and aerodynamic properties, such albedo, soil conductivity, soil moisture, surface roughness, etc. The city tends to regulate and partition the available energy and water (described in section 2.2.3) in a different manner than natural covers (Oke, 1987). Those differences are manifested as different surface, subsurface and atmospheric climates in terms of temperature, humidity and wind speed profiles creating spatial discontinuity and horizontal gradients. Near the surface at the boundaries between the fields these gradients are greatest and horizontal interactions occurs. The climatic response to these spatial variations in surface is further complicated if complicated topography is present.

2.1.2 The urban boundary layer height

The UBL, in comparison with the 'rural' atmospheric boundary layer (ABL), is characterised by greatly enhanced mixing and Mixing Heights (MH), resulting from both the large surface roughness and increased surface heating. So, the UBL is often considered as a special case of the ABL over a very non-homogenous terrain with specific characteristics.

The MH is necessary regarding the dispersion of pollution within the canopy and is an important parameter for practically all air pollution applications at the mesoscale and urban scale. Most dispersion models require an estimate of the MH so that any effective limit on vertical spread can be modelled. Its effect is most important when it is shallow, whereby pollutants may be trapped near the ground, leading to high local concentrations, while elevated plumes might be unable to reach the ground. MH estimates may be input to models, or calculated by specific routines within models. Despite progress in numerical turbulent modelling during the last decades, the MH is still one major uncertainty for most air quality models (Piringer *et al.*, 2007).

Concerning the methodology of MH determination, fundamental work has been done by COST-710 (Seibert *et al.*, 1998). COST-715 investigating urban modifications on the MH, both by measurements and parameterisations, and carried out a profound urban-rural intercomparison study for the city of Bologna under different stability conditions (Piringuer and Joffre, 2005). Both from radiosoundings and from numerical modelling there is evidence of increased MH over urban areas compared to their rural surroundings. The urban-rural intercomparison for Bologna resulted in a good internal consistency between the various schemes applied, whilst the sodar cluster of MH values clearly departs from the latter. However, with a careful sodar data analysis, a plausible average daily course of MH can be delineated.

The UBL height is an important parameter for daytime urban heat island generation and urban-breeze development as pointed out in Chapters 2, 3 and 4.

2.2 The Urban Heat Island

The Urban Heat Island (UHI) is defined as the excess of temperature observed frequently in a metropolitan area in comparison with the surrounding area. Is a wellknown characteristic of the urban micro-climate.

2.2.1 Diurnal cycle

The UHI has a typical daily cycle: it increases during the late afternoon and reaches its maximum during the night (5-8ºC for a medium-size European city; Oke, 1982) decreasing after dawn and generally reaching a minimum value during the morning hours being possible to reach negative values (-1ºC, city centre cooler than it surroundings). After that it starts to increase again. The warmth is accumulated reaching 1-2ºC during daytime (Shea and Auer, 1978; Yoshikado, 1992; Hidalgo *et al.,* 2008a).

The causes in the UHI formation are different under night-time and daytime conditions:

- During the night, a stable layer of air generally forms in rural areas, due to surface cooling (Oke, 1982). Under calm wind conditions (i.e. conditions favourable to the formation of the UHI), there is no mixing of the air by wind shear and the nocturnal stable layer inversion is strong. This nocturnal inversion can reach a few hundred meters in height. Over a city, however, the SEB is modified and the air is heated by the surface. This reduces the cooling of the atmosphere but is not strong enough to prevent it. However, it is sufficient to maintain mixing with the air above by dry convection. This leads to the development of a neutral or slightly unstable turbulent layer above the city (Figure 1.5). Therefore, during the night, this ambient stability plays a key role in determining both the UHI intensity and the strength of circulation (Scheffler, 1978, 1979; Vukovich and Dunn, 1978; Richardone, 1989).

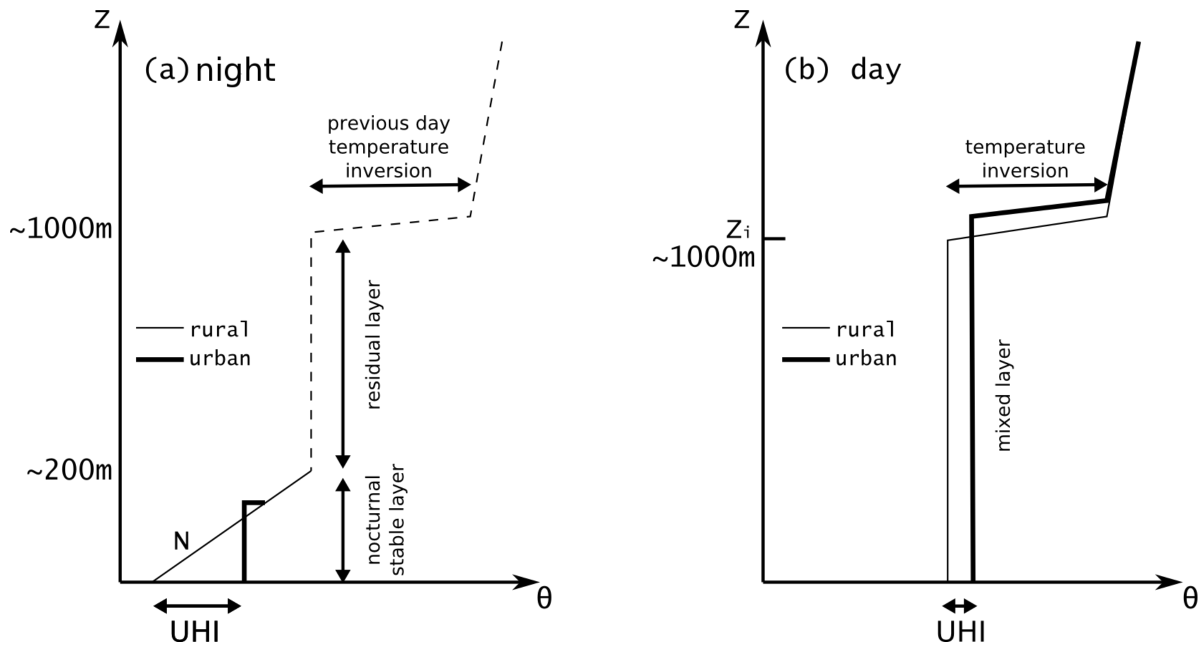

Fig 1.5: Schematic representation of the potential temperature profiles associated to the urban heat island (a) during the nigth, and (b) during the day. Thin lines are for rural profiles, bold ones for urban profiles. The dashed line in the night case represent the typical structure of the atmosphere above the nocturnal stable layer.

- During the day, the structure of the lower atmosphere is completely different from its structure at night. In the countryside, the heating of the surface by the sun in the morning produces a heat flux towards the air above that is sufficient, firstly, to destroy the nocturnal stable layer and, secondly, to mix the air (the so-called 'mixed layer', Figure 1.5) by turbulence to a much higher altitude (z_i), where a capping temperature inversion occurs. This temperature inversion is linked, not to the nocturnal stable layer (which is near the surface), but more to the previous day's capping inversion (which is still present above the nocturnal inversion, shown by dashed lines on Figure 1.5), to the general meteorological situation and the total heating of the air by the surface during the day.

  The presence of a city will modify the SEB by heating the atmosphere above it. However, this modification only represents a relatively minor modification of the countryside mixed layer: the UBL will be a little warmer (the daytime UHI), a little more turbulent, and extend slightly higher. Under favourable weather conditions, the daytime UHI can initiate local circulations.

2.2.2 The UHI is modified in function of the meteorological context

The UHI effects can be reduced or even disappear under certain regional weather conditions:

- In presence of strong winds the temperature contrast is reduced by mixing of the city and rural air as demonstrated by Sundborg (1950).

- Large amounts of clouds blocks the solar incident radiation reducing the diurnal surface heating (Sundborg, 1950).
- Raining periods also decrease UHI intensity (Yagüe and Zurita, 1991; Runnals and Oke, 2000).
- Seasons cycle also affects the UHI occurrence frequency (Jauregui, 1997; Kim and Baik, 2002).

Numerous studies show the effects of anthropogenic warming on local and regional temperatures in many diverse latitudes. Block *et al.*, (2004) showed effects across central Europe, Zhou *et al.* (2004) and He *et al.* (2005) across China, Velazquez-Lozada *et al.* (2006) across San Juan, Puerto Rico and Hinkel *et al.* (2003) even in the village of Barrow, Alaska. In all cases, the warming was greatest at night and in higher latitudes, mainly in winter.

2.2.3 Causes of UHI the generation

As population centres grow they tend to modify a greater and greater area of land and have a corresponding increase in average temperature (Oke, 1983). Oke (1973) finds evidence that the UHI (in ˚C) increases according to the formula

$$UHI = 0.73 \log_{10}(\boldsymbol{P})$$

where ***P*** denotes population.

The processes conducting to the UHI have been inferred through urban field campaigns focused on the exchanges of energy between the urban surface and the atmosphere (Nuñez and Oke, 1977; Cleugh and Oke, 1986; Oke *et al.*, 1999) and the development of numerical models dedicated to the computation of these exchanges (Arnfield, 1982; Grimmond *et al.*, 1991; Masson, 2000; Martilli *et al.*, 2002). The reason the city is warmer than the country comes down to a difference between the energy gains and losses of each region resulting on a SEB modification. Four common physical characteristics of urban areas modify the SEB and the micro-meteorological processes that occur between a surface during the day and the night in comparison with the same the phenomena in a rural area. These four characteristics are:

- **[1]** the rarefaction of vegetation and the massive use of impervious materials for buildings and pavements,
- **[2]** the ability of building materials to store and release large amount of heat within a few hours,
- **[3]** the three-dimensional geometry of the urban surface (urban canyon shape of streets),
- **[4]** the heat releases by the human activities (traffic, space heating, space cooling, industry).

During the day in rural areas most of the solar energy evaporates water from the vegetation and soil. Thus, while there is a net solar energy gain, this is compensated to some degree by evaporative cooling. In cities, where vegetation is scarce (the property **[1]** of the urban surface), the buildings, streets and sidewalks absorb the majority of solar energy input and the solar energy is almost completely transformed into heat. Then the property **[2]** leads to an enhancement of the process of heat storage in the urban materials. As a consequence of these two properties, at the end of the sunlit period, the urban materials have accumulated a higher amount of the solar energy than a typical vegetated rural area. Then, when the night comes, this large stock of energy is released to the air above and delays or reduces the air cooling in the urban canyon. Moreover, the property **[3]** further limits the cooling rate of the walls and the streets. Each (warm) wall and street of the urban canyon has a reduced sky-view factor and sees each other whereas a flat open surface (open to the sky), will cool more rapidly. Finally, the property **[4]** results in an additional source of heat in urban areas.

There are numerous studies analysing and describing UHI features by means of field experiments, numerical approaches and with laboratory models, Pigeon (2007c) made a good review of the UHI state-of-art.

2.3. Urban impact on the surface energy balance

Urbanized surface properties modify the SEB (described in section 1.2.3) resulting in atmospheric phenomenon characteristics of urban environments. The urban heat island is one of them.

Earlier work in North American cities (Grimmond and Oke, 1999a) motivated that COST-715 initiated and conducted several European urban field experiments to investigate whether similar or different perturbations of the surface energy balance partitioning compared to the rural surroundings would occur in European cities. European cities have generally denser urban cores, which should lead to even larger perturbations than reported from the former American studies.

The urban SEB may be expressed with directly measured terms (Oke, 1988):

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

Being Q^{*} the net all-wave radiation flux, Q_F the anthropogenic/combustion heat flux, Q_H and Q_E aerodynamic turbulent sensible and latent heat fluxes. The term ΔQ_S is the neat heat flux stored into or released from the canopy, including the air layer between the measurement height and the material surface, as noted by Grimmond and Oke (1999a). Under light large-scale winds the advection term,

$\Delta Q_A = \int_0^{30} \rho C_p \overline{u} \frac{\partial T}{\partial x} dz$ is negligible considering the order of magnitude of the other fluxes.

The UHI formed during daytime is the source of the daytime urban-breeze circulation central topic of this study. The analysis is then centered on this part of the SEB and UHI diurnal cycle and linked to the local circulation (dynamics) generated (an extensive analysis of the complete diurnal cycle is presented in Chapter 2).

During daytime in urban areas:

- The turbulent flux density Q_H is the primary mean of dissipating the net radiation surplus (due to building materials, 3D geometry and the heat released by the human activities (waste heat generated by energy usage: traffic, space heating or cooling, industry...)) remaining positive even into late evening (after sunset).
- As a consequence of use artificial and impervious materials for buildings and pavements, vegetation is scarce in cities and evotranspiration (Q_E) is reduced being close to zero in the city center (with no street cleaning) during summer periods.
- Sensible heat storage (ΔQ_S) by the system is also a significant term in the balance. The flux depends on the urban structure, the thermal properties of the urban materials (thermal conductivity, heat capacity), and the sun–surface–atmosphere coupling (Roberts, 2006). During daytime ΔQ_S is important to model evaporation, the convective sensible heat flux, and the boundary layer growth (Grimmond *et al.,* 1991; Roth and Oke 1994; Taha, 1997).

Under summer conditions with weak wind, this lower evapotranspiration in the city leads to a preferential channelling of energy into sensible forms (Q_H and ΔQ_S) and therefore a warming of the environment generating the UHI cited before. To summarize, under daytime conditions the surface heat flux in the countryside can be significant: at least in the morning it is sufficient to build the mixed layer, and most often, it remains positive during the entire day. However the countryside heat flux is lower than the urban one, because of a large consumption of the available solar energy for latent heat flux by the plants. This difference in the heat flux between the city and the countryside is what causes the daytime UHI key feature of the daytime urban breeze circulation.

Urban perturbations on the SEB can actually successfully be parameterised. A number of European groups developed detailed urban SEB parameterisations for mesoscale models (Masson 2000; Martilli *et al.,* 2002; Baklanov *et al.,* 2002; Best, 2005; Dandou *et al.,* 2005, Hamdi and Schayes, 2005; Dupont, 2006; Dupont and Mestayer, 2006). Preliminary studies indicate that the influence of the urban canopy, building energy flows and thermal properties, along with effective albedo reduction by radiative trapping between canyon walls, is important and needs to be properly described in models. These parameterisations will probably become operational in the near future, progress has been made within the EU project FUMAPEX (Baklanov *et al.,* 2006) initiated by COST-715. An inter-comparison exercise of existing Urban Surface Schemes coordinated from the King's College London, started at the end of 2007. A set of about thirty models is participating in this exercise aimed to evaluate the realism of urban heat exchange, computational performing and paraterizations complexity needed to obtain accurate results (http://www.kcl.ac.uk/ip/suegrimmond/model_comparison.htm).

3. The urban-breeze circulation

3.1 General features of wind dynamics in the urban boundary layer

The dynamics of convective boundary layer is very important to understand the meteorological now –casting, including the prediction of boundary layer evolution and pollution dispersion.

Speed, direction, and turbulence of wind are modified by changes in surface properties. There are essentially four characteristics of the urban surface whose variations cause changes in wind field near the ground: surface roughness, topography, shelter from nearby buildings, obstacles, and thermal and moisture properties of the surface (Radics, 2002). When air flows over different surfaces, each have specific modification effects on the flow. Some act to increase wind speed, others, to decrease it and all acting to alter wind directions from the overriding weather pattern. Such influences act on weather spatial scales which range in size from tens of kilometres down to metres and less (Oke, 1987).

As the air flows from the rural environment to the urban environment, it must adjust to the new boundary conditions (Figure 1.6). The roughness of the city acts to slow the wind, through aerodynamic drag, and increase its turbulence. Its impacts are related to the height of the roughness elements: trees, buildings, etc. that make up the city. Then in a general way the wind speed in the canopy layer significantly decreases relative to the undirsturbed wind speed. This was first observed and documented by Kremser (1909).

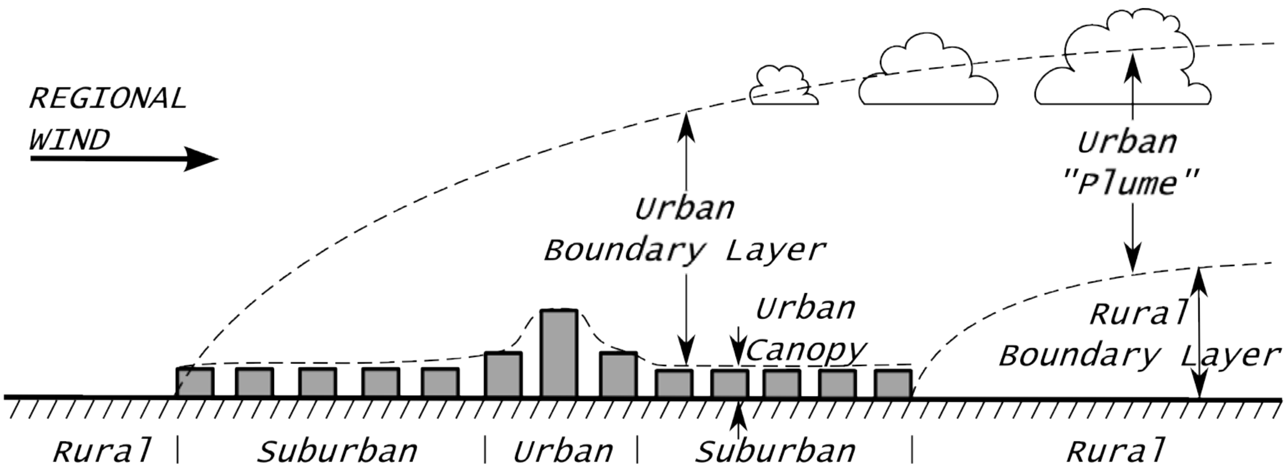

Fig. 1.6: Schematic representation of the Urban Boundary Layer in case of existent large-scale mean wind for a hinterland city.

Oke (1987) characterized the wind variation with height over cities by defining the two specific sublayers described in point 2.1, the canopy sublayer and the UBL wich exist over the roof tops. The canopy sublayer has its own flow field, driven and determined by the interaction with the local features. A very detailed study of the problems related to the air flow in the urban canopy layer is given by Landsberg (1981).

This study is devoted to the general characteristics of the air flow on the UBL (over the canopy layer) under anticyclonic conditions. Under this weather conditions this heating can propagate in the lower atmosphere (in the whole layer) and then downstream of the city (depending on the wind direction). This is the so-called “urban plume” (Oke, 1987). When the wind is strong or in case of rain, the impact of the city on lower atmosphere dynamics are negligible, and only the emission of pollutants and their chemical transformation downstream of the city remains. However, when the winds are moderate like in anticyclonic conditions, the urban plume can transport the heat from the city center to the surroundings. If the mean wind is weak, then an urban-breeze can develop. This is one of the two cases described by Oke (1987) where the air speed in urban areas may be higher than in rural areas. The other one is when the higth speed air layers are either deflected downwards by tall buildings or chanelled as 'jets' along canyons in the same direction as the flow.

3.2. Urban-breeze.Terminology and definition

This atmospheric phenomenon had not an unified terminology in the literature and evolved during the years. In the seventies the first studies dealing with the dynamic impact of the UHI on the ABL called it ***UHI convection*** (Olfe and Lee, 1971), or ***Atmospheric convection due to the UHI effect*** (Kimura, 1975). Oke

(1987) talks about the ***Heat-island thermal breeze*** and other authors (Yoshikado, 1992; Lu e*t al.*, 1997; Kurbatskii, 2000) use ***Heat Island Circulation (HIC)*** or ***Urban Heat Island Circulation (UHIC)*** appellation. More recent studies name it ***UHI-induced convection, circulation or convergence*** as Baik (2000). Finally, Lemonsu (2002) designates the ***Urban-breeze circulation*** in analogy with the *sea-breeze circulation* of coastal environments. The last one is the terminology chosen and used in this study.

The terms cited before refers to a closed circulation associated with the UHI characterized by strong updraft motion at the city center, by horizontal convergent flow above the heated surface, and by divergent flow at the elevated layers (Figure 1.7). A slow downdraft far from the city closes the circulation. If the canopy portion of the inflow is strong enough to overcome the frictional drag of the canyon walls then winds may be slightly greater than in surrounding rural areas. Absent or weak synoptic winds, high insulation and a well developed convective boundary layer (daytime conditions) favoured this type of circulation.

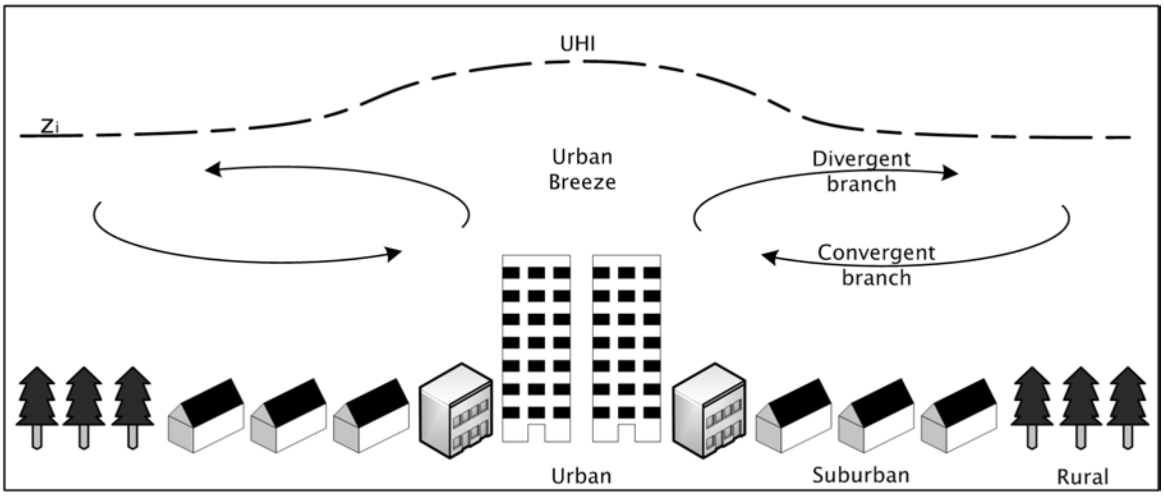

Fig. 1.7: Schematic representation of the Urban Boundary Layer under weak large-scale wind in a hinterland city.

3.3. Motivations and approaches of this study

The UHI, is easily observable by a meteorological surface network with a good horizontal distribution. However, to describe the urban-breeze circulation it's necessary to characterize other effects, as the convergent movements of air over the city centre, which can not be measured easily using standard equipment. For this, almost no observations exist of this phenomenon.

Most of existing studies are basically centred on the UHI interaction with the daytime sea breeze (Carisimo *et al.*, 1996; Yoshikado, 1992; Cenedesse, 2003) but most of European capitals, where financial interests and population are concentrated, are situated inland at tens of kilometres from the coast. There are studies centred on local circulations over a heated surface (without oceanic influence) (Olfe and Lee, 1971; Lin and Smith, 1986; Lin, 1987; Lu *et al.,* 1997a; Lu *et al.,* 1997b; Richiardone and Brusasca, 1989; Baik, 1992; Yoshikado, 1992; Baik and Chu, 1997 or Baik, 2001 etc.) but they are concerned with night-time conditions with a stable atmosphere. Chandler (1961, 1965) studied the relation between surface breeze and UHI for Leiceister and London respectively, finding convergences stronger during the night. This results are in opposition with some studies over St. Louis (Shreffler, 1978, 1979). Actually, no study has focused in depth on daytime urban-breeze circulation and a comprehensive, fundamental investigation is still necessary.

In **Chapter 2** an experimental approach of the urban-breeze is done using experimental data from the CAPITOUL campaign (Toulouse, France 2004-2005). To quantify the unmeasured 3-D mesoscale urban effects, high resolution numerical simulations are useful to complete and validate the observed information. A numerical approach using the non-hydrostatic atmospheric model Meso-NH (Lafore *et al.*, 1998) coupled with the urban surface scheme TEB (Masson, 2000) is done in **Chapter 3**. Finally a theoretical study of the thermodynamic profiles of temperature and wind is done in **Chapter 4** where a simple set of equations describing the urban-breeze features is presented.

This PhD thesis is the result of a collaboration between the TURBAU from the CNRM/Météo-France (Toulouse, France) and the Atmospheric group (FA09) of the Vigo University (Ourense, Spain). This work was developed under the hosting of the TURBAU team during the two first years and the FA09 group during the last year. The author has request the Doctoral School of the Paul Sabatier University the European label for this PhD work.

Chapter 2

The CAPITOUL campaign. An Observational Approach to the Urban-Breeze Circulation

In the field of urban measurements, the attention was historically centered on those measurements that support weather forecasting for National Meteorological Services. This focus required measurements to define meteorological conditions and air quality. In general, monitoring air pollution served three purposes: assessment of the situation, to determine compliance to legislation, and to provide information in support of mitigation strategies. For each of these purposes, the monitoring data alone are insufficient and the data therefore is now days used to both drive air pollution models, and support the research necessary to improve model performance.

As interest in urban climate grows, international organitations as WMO increased attention on meteorological and climatological aspects of urban environments including it in their programmes. For example in 1995 at the 12th World Meteorological Congress in Geneva, and subsequently at Habitat II in Istanbul, WMO committed gave high priority to the delivery of better services to cities. In GURME (GAW Urban Research Meteorology and Environment project) workshop held in Beijing, (China, 1999) an urban meteorological data collecting system for a number of big cities was planned. This system included intensified observations of: UV radiation, pollen, and boundary layer parameters. These new data, in addition to the conventional meteorological elements, will be stored in a special data base.

If that is to be meaningful, more and better urban observing stations are required. The placement of stations needed to be made in reference to the utility of the data by models and representativeness of the observations. Before National Meteorological Services investe in this infrastructure, to optimize the number and placement of monitoring sites, and which measurements are needed at each site, guidelines protocols must been available for the monitoring systems designer. As progress in knowledge was done in fields of urban meteorology, climatology and hydrology about the physical basis of urban atmospheres, and the technical requirements for measurement, useful Guides to observing practice has been appeared: Gysegem (1983), WMO (1983a), WMO (1983b), Oke (1984), Oke(2004).

This guidelines are also useful to proper design experimental campaigns exclusively oriented for research purposes. The number of urban experimental fields has been increased with campaigns in the principal cities of the world: “Metromex” in St Louis (USA, 1974-1976, Changnon, 1981), Vancouver (Canada, 1976), Mexico city (Mexico). Urban european experiments: Uppsala (Swedden, 1981), “Medcaphot-Trace” in Athènes (Greece, Klemm, 1995), in 2002 the Basel Urban Boundary Layer Experiment (BUBBLE, Rotach *et al.,* 2005); and studies in the cities of Bologna, Birmingham, Athens, Copenhagen, Cracow, Helsinki, and Hannover (Piringer and Joffre, 2005). COST-715 also initiated the EU-project FUMAPEX (Integrated systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure), conducted between 2002 and 2005 (Baklanov, 2006).

In France a big effort to study urban climate of it main cities has been done. Experimental campaigns in Paris (ECLAP, Nov. 1994 - Mars 1995; Dupont, 1999), ESQUIF (Paris, Menut *et al.*, 2000), Marseille (UBL-ESCOMPTE, 2001, Mestayer *et al.,* 2005)) and recently in Toulouse (CAPITOUL, 2004-2005; Masson *et al.*, 2008) has been carried out thanks to collaborations at the national and international levels.

The experimental campaign CAPITOUL (Canopy and Aerosol Particles Interactions in Toulouse Urban Layer) is presented in article form in Annexe 1. This article has been recently accepted in a thematic number of the review “Meteorology and Atmospheric physics” (Springer) about the campaign. The article is now considered *in press*. This Chapter 2 contains un experimental approach to the urban-breeze circulation submitted to the same review. At the time this manuscript is written, the article is acceped and in final version . Thanks to the CAPITOUL observations an urban-breeze episode could be documented for a sunny summer day where the sensible heat flux during the afternoon was approximately 250 W m^{-2} larger in the city than in the countryside leading a daytime UHI of +1 °C. This study shows the relative roles of the SEB components and the ABL structure for the development of the low-level airflow convergence towards the city.

Urban-Breeze Circulation during the CAPITOUL Experiment: Observational Data Analysis Approach

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Abstract: An experimental study focused on the urban-breeze circulation observed in Toulouse, South-West of France, during the Intensive Observation Period number 5 (IOP5, 3rd and 4th July 2004) of the CAPITOUL experiment (Feb. 2004 to Feb. 2005) is presented. The influence of the urban breeze circulation on the structure and the dynamics of the Atmospheric Boundary Layer is analysed by using ground stations, wind profilers (UHF radar), radio soundings and aircraft data. The IOP5 is a summertime anticyclonic situation with low wind, strong insulation and a deep boundary layer with a sheared wind profile.

The temporal and spatial relationship between the Surface Energy Balance (SEB), the diurnal evolution of the surface temperature and the dynamics of the airflow within the mixed layer are studied for urban and rural sites. The vertical and horizontal structure of the urban heat island are analysed from both surface stations and aircraft data. The nocturnal urban heat island reaches 5 °C. In the early morning, the city air becomes 1°C cooler than in the countryside (due to efficient heat storage and building shade on the city urban canopy), then warmer again (1°C) in the afternoon, due to negligible evaporation and strong sensible heat flux in the city. The daytime heat island is also present in altitude, being localized above the city centre at 350 m of height (1°C) and advected to leeward at 1100 m of height (0.5°C).

This diurnal heat island is associated to an urban-breeze circulation characterized by a surface convergence towards the city at low levels and a divergence in upper boundary layer. The urban breeze grows in intensity from 2 m s^{-1} (at 12.00 UTC) to 5-6 m s^{-1} (at 18.00 UTC). Aircraft measurements show that the urban breeze horizontal extension is 2 to 3 times larger than the city size.

Keywords: Urban-breeze, heat island, aircraft data, urban boundary layer, CAPITOUL experiment

1. Introduction

The urban-breeze is a mesoscale phenomenon (Oke, 2005) characterized by a surface convergent flow from the countryside to the city centre, induced by a horizontal temperature gradient. This dynamical circulation at low levels is completed by a divergent flow at the top of the Atmospheric Boundary Layer (ABL).

Urban-breeze is defined theoretically by analogy with the sea-breeze circulation in coastal environments. The sea-breeze is a well documented mesoscale flow caused by unequal land-sea diurnal heating cycle that blows from the sea to the land due to this differential heating. The horizontal structure is characterized by the land surface warmer than the sea surface with a maximum gradient in the late afternoon. Warmer air rises over the land and a local onshore circulation starts, with colder air from the sea being drawn in over the land. At the same time, due to the thermally induced horizontal pressure gradient, the ascending air returns seaward as the upper return current. Its vertical extension is generally restricted to the lowest 1-2 km of the atmosphere, therefore the sea breeze is strongly influenced by the boundary layer processes. In coastal cities this phenomenon has a strong influence on the urban boundary layer and has been well documented (Fisher (1960), Walsh (1974), Atkinson (1981), Rotunno (1983), Nakane (1986), Niino (1987), Finkele (1995), Feliks (1994), Lemonsu (2004c), Lemonsu *et al.* (2006a, 2006b), Augustin (2006)). They explore its properties and structure, its dynamics and its overall impact on the air quality of coastal cities. However, few is known on the dynamics and structure of the urban-breeze circulation in an inland city. Only one study (Wong and Dirks, 1978) analyses urban thermally induced motions using observational data for an inland city. It shows a convergence towards the city at low level in the boundary layer over St. Louis using aircraft data from the METROMEX campaign (Changnon, 1981).

The different responses of the land surface and the urbanized surface to the diurnal cycle create the Urban Heat Island (UHI), which is the source of the urban-breeze circulation. The UHI is easily detectable by a meteorological surface network with a good horizontal distribution. However, to describe the urban-breeze it is necessary to characterize other effects, like the convergent flow of air toward the city centre, which can not be measured easily using standard equipment. For this, numerical simulations are used by Lemonsu and Masson (2002) as a strategy to study this phenomenon and to quantify the unmeasured 3-D mesoscale urban effects.

Urban-breeze can affect the transfer of pollution from interurban industrial areas into the city centre. A better understanding of these breeze circulations is of primary importance in the prediction of pollution peaks and the evaluation of air quality policy in the cities. Furthermore under moist conditions the urban breeze thermodynamics can provide a favourable environment for convective thunderstorm over the urban area and precipitation downwind resulting in more lightning activity and heavier precipitations. Sheperd (2005) provides a concise review of recent (1990–present) studies related to how the urban environment affects precipitation.

During the CAPITOUL experiment, meteorological conditions and thermo-dynamical properties were provided by different instruments that supplied complementary space and time information. This allows us to study both, the horizontal ground characteristics and the 3D properties of the breeze, using wind profilers, radio soundings and aircraft data.

The work presented in this paper is an experimental study focused on the urban-breeze circulation observed in the city of Toulouse, in the South-West of France, during the Intensive Observation Period number 5 (IOP5, 3rd and 4th July 2004) of the CAPITOUL experiment (Feb. 2004 to Feb. 2005, Masson *et al.,* 2008). The analyse focuses on the city influence on the structure and the dynamics of the ABL. The IOP5 corresponds to a summertime anticyclonic situation with low wind and high insulation, meteorological conditions which are favourable to breezes episodes.

2. Observational Network

The Canopy and Aerosol Particles Interaction in Toulouse Urban Layer (CAPITOUL) experiment took place over the city of Toulouse, France, from February 2004 to February 2005. In this context, 15 IOPs were carried out during a year to characterize the diverse interactions (thermodynamically and chemically) between the city and the atmosphere under a wide range of meteorological conditions. An extensive description is presented in Masson *et al.*, 2008.

The CAPITOUL experiment had a broad experimental deployment in urban and rural zones, providing boundary layer characteristics for both environments. For this study, ground stations, a wind profiler (Ultra-High Frequency (UHF) radar), radio soundings and aircraft data are used.

2.1 Surface Network in the Area of Study

The surface network was placed in different Urban Climate Zones (UCZ) according to recommendations of Oke (2005) and was composed of (Figure 1):

An assembly of 21 light stations recording temperature and relative humidity with 12 minutes sampling, situated in the city centre and in the suburban areas of Toulouse.

A network of synoptical ground stations of Meteo-France measured the horizontal wind velocities at a height of 10 m. The temperature and relative humidity levels were recorded at a height of 2 m in a 10 km radius from the city centre.

An instrumented pneumatic tower situated on the old core of the city is considered as the reference station chosen to describe the properties of the city centre of Toulouse. This central tower, which is 30 m high, was situated on the roof of a building (situated 20 m above the ground). Temperature, relative humidity, wind speed, pressure, upward and downward global short- and long-wave radiation, and the turbulent fluxes measurements were recorded. The turbulent fluxes are computed on 30 minutes period with eddy covariance techniques.

In addition, measurements of the Surface Energy Balance (SEB) (measurements of radiation + turbulent fluxes) with a 30 minutes sampling were also recorded using two flux stations situated for the first one at 15 km south-west (Fauga, situated in a grassland area) and for the second one at 40 km north-west of Toulouse (Saint-Sardos, situated in a irrigated maize crop). The stations were equipped with the same instrumentation as the central site. Both types of covers are common around Toulouse area.

The urban stations surroundings are described using a 100 m resolution urban database produced from 0.25 m resolution aerial ortho-rectified photography and a 2D and 3D vectorial database. A semi-automatic classification (GRASS 6.0, Open Source GIS) is applied on the photography to separate the environment into four surface categories: high vegetation, low vegetation, roofs and roads. The sky view factor is calculated for each station from a hemispheric picture. The surface network characteristics and emplacement are shown in Table 1 and Figure 1.

Owing to this data base and to the sky view factor, four classes of urbanization are chosen: urban area, residential suburban area, non-residential suburban area and rural area.

2.2 Boundary layer Instrumentation

The study uses observations collected by radio soundings, UHF-band wind profiler, and an instrumented aircraft. This allowed a quasi-continuous remote monitoring of the boundary layer and of the low troposphere during the two days of the IOP.

- Two sites were equipped with radio sounding systems. One located at Merville, a rural zone situated at approximately 15 km north-west of the city centre. The second one, the Valade's site, was situated in Toulouse's city centre. Radio soundings were performed four times per day at 03.30, 08.00, 13.00

and 18.00 UTC.

- The DEGREWIND PCL1300 wind profiler was situated in the city centre at 100 m of the central tower. Measures of radar reflectivity, wind force, wind direction and its vertical velocity were registered with a 75 m vertical resolution, 4000 m vertical coverage and 6 minutes temporal resolution. Radar data were compared with the vertical wind profiles from the radio sounding in the city centre to validate the quality of the measurements.
- The Météo-France instrumented aircraft *Piper Aztec* performed two flights per day during this IOP (AZ0423 and AZ0424 on the 3rd July and AZ0425 and AZ0426 on the 4th July). Three horizontal flight legs were made over the city centre and the rural zones at an altitude of 350, 1100 and 1600 m. The following aircraft data set is used in this study: the potential temperature, the water vapour mixed ratio, the wind force and direction (the sampling period was 1Hz which, given the speed of the plane, is equivalent to a spatial resolution of 70 m).

3. Meteorological context of this IOP

The study is focused on the thermal and the dynamical properties of the ABL for the 4th July 2004 over the city of Toulouse and its surrounding country. To improve the nocturnal process comprehension, for certain analyses, we extend the study to the 3rd July 2004.

The synoptic situation allowed the development of an anticyclone in the South of the country. A high pressure ridge, from the Atlantic Ocean to the North of Europe was present during the period of study. Toulouse was situated in a barometric marsh which evolved into a depresionary zone during the 5th July. The result of this stability was a very sunny period. The presence of a little Cumuli in the morning of the 3rd July, between 08.00 to 12.00 UTC, limits the fraction of insulation to 88%. The net radiation measured at the central tower at midday was 600 W m^{-2}. During the 4th July there were no clouds, the fraction of insulation for this day being of 91%. The period presents high thermal amplitude, particularly on the 4th July with a minimum temperature of 11 °C during night-time and a maximum of 34 °C.

The boundary layer wind was characterized by a weak velocity profile varying from 0.5 m s^{-1} in the night of 3rd to 4th July to a maximum of 6 m s^{-1} in the late afternoon of the 4th July. The wind was blowing from north-west on the 3rd July. The first change of the surface wind from north-west to the south-east was at 21.00 UTC. This creates a region of a weak flow in the transition layer between the south-easterly flow near the surface to the north-westerly flow at upper-levels (Figure 2). A second change in the surface wind towards west occurred after 20.00 UTC on the 4th July, when a westerly air mass arrives over Toulouse. This change of direction in the mean flow is captured by the UHF radar, situated in the city centre, in the firsts 1500 m of the ABL (Figure 2).

The 15 days preceding the experiment corresponded to a cloudy period with no rain, the accumulated precipitation was only 1 mm. As a consequence, there was no water available for evaporation on urban surfaces while the soil is still sufficiently moist to enable evapotranspiration by the vegetation. On the 4th July the specific humidity in the ABL had a constant value of 7 g kg^{-1} until late afternoon. At 20.00 UTC the new westerly air mass induced an increase of the specific humidity to a maximum 10 g kg^{-1} near the surface.

4. Temporal and spatial relations between thermodynamics fields and surface features

As described by Oke (1981), Oke (1987), Unger (2001) and Eliasson and Svensson (2003), the diurnal cycle and the horizontal pattern of temperature and moisture as well as the surface fluxes have a strong dependence on varied factors, such as for example: the surface geometry (aspect ratio, sky view-factor, roughness length and albedo), the properties of artificial materials in urban centres (urban cover fraction, moisture availability...) and the anthropogenic emissions. In this section, the spatial and temporal evolution of these thermodynamic fields are analysed for the 4th July 2004.

4.1 Surface Energy Balance (SEB)

The surface energy balance is significantly altered by urban areas (White (1978), Grimmond (1999), Oke (1999)). The difference of SEB between the city and the rural zones affects the whole boundary layer, its stability, thermodynamic properties and the mixing layer height (Christen and Vogt, 2004). The modified urban SEB is the UHI source, which is the key element of the urban-breeze circulation development.

During this IOP three experimental sites (two rural and one urban) computed the SEB on 30 minutes period. The measured turbulent flux densities are an area-averaged response of the surface. The urban site describes an integrated flux from an area representative of the local scale, 'urban neighbourhood' (10^4-10^6 m^2) (Christen and Vogt, 2004). Thanks to the Toulouse homogeneity in terms of construction density, building type and materials, although it is a simplification, we will consider this value as representative for the entire city centre.

The energy balance at the top of the street canyon is described by Oke (1988) as:

$$Q*+Q_F=Q_{LE}+Q_H+\Delta Q_s+\Delta Q_A$$

The flux densities of net all-wave radiation $Q*$, upward sensible heat $Q_H=\rho C_p\overline{w'\theta'}$ and upward latent heat $Q_{LE}=\rho L_v\overline{w'q'}$ at the surface are directly measured. The latter two are calculated using the eddy-correlation method. Following Pigeon *et al.* (2007a), we can estimate the advection term (ΔQ_A) as $\int_0^{30}\rho C_p\overline{u}\frac{\partial T}{\partial x}dz$.

From the measurement network, $\overline{u}\le 5ms^{-1}$, $\Delta T=1\mathrm{K}$ and $\Delta x=10^4 m$. Consequently, $\Delta Q_A=6Wm^{-2}$ and can be ignored in the SEB considering the order of magnitude of the other fluxes.

Finally the sum of the heat storage (ΔQ_s , positive for warming) and the anthropogenic heat flux (Q_F) is estimated from the residual of the budget as:

$$R = \Delta Q_s - Q_F = Q* - (Q_{LE} + Q_H)$$

The 4th July 2004 is a cloudless day at all sites (Figure 3) with maximum net all-wave radiation $Q*$ of 600-650 W m^{-2} at 12.00 UTC (LT=local summer time = UTC + 2h). The major differences of $Q*$ are present at night caused by the differences on the storage term for both sites. We assume that in summer, for the city of Toulouse (Pigeon, 2007b), the heat stored ΔQ_s is the dominant term of the residual component. The heat storage depends on materials nature and moist availability, for this reason urbanised areas and rural areas present thus different values of ΔQ_s .

This solar energy is distributed in the different terms of the energy balance. For the rural site Saint Sardos (Figure 3b), during the night from 3rd to 4h July the sensible and the latent flux densities are zero until the sunshine. Radiative loss ($Q*$) by infra-red radiation creates negative values of the residual term ($R = -40\, Wm^{-2}$, directed from the ground to the atmosphere). During the day the sensible heat flux increases fast in the morning with a maximum value of 150 W m^{-2} at 11.30 UTC, then decreases nearly to zero during the afternoon due to evaporation cooling. This rural site is situated in a maize crop irrigated during the afternoon. The latent flux Q_{LE} reaches its maximum value 500 W m^{-2} at 15.00 UTC. Sunset, around 18.00 UTC, creates a gradient of temperature as the atmosphere is hotter than the ground. Then, the sensible heat flux lowers and becomes negative reaching -50 W m^{-2} after 20.00 UTC.

Even at the Fauga site (Figure 3c), which was non-irrigated grassland, Q_{LE} reaches a maximum of 220 W m^{-2} during the morning and Q_H has a constant value of 90 W m^{-1} between 12.00 to 16.00 UTC decreasing to zero in late afternoon. The Bowen ratio is higher than 0.5 and indicates that the soil is moist.

In the city (Figure 3a), during the night from 3rd to 4th July, the sensible flux density, in contrast to the rural sites, presents small positive values. During the afternoon, the sensible heat flux value reaches a mean value of 300 W m^{-2}. Mid-latitude cities with negligible vegetation and irrigation show less evapotranspiration than their surroundings and during this very sunny day, Q_{LE} remains lower than 50 W m^{-2} which is very weak. This reduced daytime evapotranspiration (Q_{LE}) in the urban area results in increased magnitudes of sensible heat (Q_H) and heat storage in the construction materials (ΔQ_s) over the entire day. In the morning the heat is mainly stored in the urban fabric and is released as turbulent sensible heat into the atmosphere in the late afternoon and evening (Oke, 1988).

To summarize, during the period of the breeze (12.00 to 18.00 UTC), the sensible heat flux in the rural sites is very weak (close to zero at Saint Sardos and 90 W m^{-2} at Fauga) regardless of the surface cover (an irrigated maize crop land at Saint-Sardos and a grassland area at Fauga). The city centre presents strong Q_H positive values (300 W m^{-2}) during the same period heating the air above the city and creating a positive anomaly of temperature between the city and the country, which is a key process of the urban-breeze circulation.

4.2 Urban Heat Island

Turbulent flux differences on Q_H and Q_{LE} between urban and rural zones produce the differences in the diurnal evolution of temperature and relative humidity. The diurnal cycle of rural and urban potential temperature at the surface is analysed in this section. The singular measurements at the ground stations are representative only of a small area around the station (local scale). To obtain a good representation of the diurnal cycle of the surface potential temperature and the UHI at the "city scale", the data from the assembly of 21 temperature and relative humidity light stations situated in the city centre and suburban areas of Toulouse were averaged according to 4 classes of urbanization (urban area, residential suburban area, non-residential suburban area and rural area, see section 2).

Toulouse presents a diurnal cycle of surface potential temperature typical for an urbanised environment (Figure 4a). In the diurnal course, urban-rural differences are strongest at night. The nocturnal cooling of the surface is slighter in the city-centre than in the rural zone, due to the liberation of the energy stored in the urban materials during the day and the reduced radiative cooling inside the urban canyons. The night from 3rd to 4th July presents a nocturnal urban heat island (Oke, 1987) between 3°C and 5°C (Figure 4b).

In the city, a large part of the solar energy is stored in the urban materials. This term is dominant during the morning. Moreover measurements were made inside of the urban canyon and are influenced by building shade, for these reasons the atmospheric heating inside of the urban canopy is delayed in comparison with the rural zones creating an urban cool island (Oke, 1987). The 4th July the cool island in the city starts with the daybreak at 06.00 UTC and finish at 10.00 UTC. The morning heating delay in the city centre is significant between 08.00 to 09.00 UTC with an amplitude of 0.5°C .

After midday, the difference of temperature between the city and the surrounding country becomes positive creating a weak heat island of 1 to 1.5°C amplitude. In average, the temperature reaches its maximum in the rural (33°C) and urbanised zones (34°C) at the same approximate time, i.e 15.00 UTC. The potential temperature starts to diminish in the rural area at 16.00 UTC and in the urbanised area at 18.00 UTC. This diurnal heat island is an important element for the urban-breeze generation and for its persistence during this day.

5. The Urban-breeze circulation

5.1 Vertical structure of the ABL

For our case study, i.e. anticyclonic summer situation in a flat continental area, the vertical diurnal development of the convective ABL is mainly driven by the ground heating. All morning long, the air was warmed and homogenized by turbulence. In the first hours after dawn, this heating was slower in the city centre than in the rural zone creating the cool island cited formerly.

At 13.00 UTC, the vertical structure is the following:

The vertical profiles of potential temperature from the radio sounding at the urban and rural (Merville) sites (Figure 5) exhibit an unstable boundary layer, with a first inversion of temperature at the height of 1000 m over the rural zone and of 1100 m over the city, corresponding to the layer where the wind turns from SE to NW (Figure 2). The rural site (Merville) is situated leeward of the city up to this level and is influenced by the urban UHI which is advected toward north-west (Figure 7a). From 10.00 UTC on, the heating of the city centre boundary layer has been faster than at the Merville site. The atmospheric column over the city is 1°C warmer than the column over the rural site.

The top of ABL, defined as the entrainment zone top height, is approximately at 1600-1700 m of height from the ground level:

- In the temperature profile from the RS, it corresponds to the summit of the second temperature inversion.
- From the aircraft measurements, it can be inferred that the ABL top is below 1750 m since from this flight level on, there is no turbulence signal on temperature time series. Moreover, given the weak turbulent signal recorded during flight P3 (Figure 6b), it is deduced that the 1650 m level is in the entrainment zone (reached by only a few thermal updrafts penetrating through the free atmosphere from the convective mixed layer).
- The measurements from the UHF radar (Figure 2) show a perturbation on the large scale wind field up to 2000m and the radar reflectivity situate this transition layer at 1700m (yellow colour).

5.2 Identification of the urban-breeze circulation by the analysis of the aircraft data

Aircraft flew twice during this day providing an horizontal appreciation of the phenomenon. In this study we will focus on the afternoon flight performed between 12.08 and 15.26 UTC.

5.2.1 Flight description

The flight was divided in 3 main legs:

- P1 (13.33 to 14.15 UTC): flight leg crossing the urban area and its surrounding country along a NW-SE axis at 350 m.
- P2 (14.51 to 15.20 UTC): flight leg focused on the urban area at 1100 m
- P3 (12.32 to 13.11 UTC): flight leg crossing the area from the NW-SE axis at 1650 m.

The aircraft legs are superposed over a map of Toulouse and its surroundings (Figure 7(a, b and c)).

5.2.2. Potential temperature analysis

The perturbation on potential temperature created by the city (anomaly) is calculated for each flight leg. We consider that a flight leg is in the ABL when the temperature signal is dominated by the high frequency created by the turbulent motions (Figure 6b). If the flight leg is sufficiently long, the signal of the diurnal evolution is also visible. A flight leg situated outside of the ABL has a weaker frequency variation and its diurnal cycle is negligible.

The anomaly of potential temperature field is calculated taking into account the above-mentioned characteristics. For the flight legs at 350 and 1100 m (inside the mixing layer), the diurnal trend of the temperature is removed using a least-square fit function. The tendency of 2°C h^{-1} at 350 m and 1°C h^{-1} at 1100 m compares well with the diurnal trend of temperature estimated from the surface network (temperature averaged by zones) during the same period (1.5°C h^{-1}).

The flight leg P1 shows a clear diurnal evolution of 1.5°C and a relative maximum (Figure 6b) corresponding to the passage above the city. When this trend of 1.5°C is removed from the temperature data, the result is a 1°C amplitude heat island over the city (Figure 7a) in agreement with the radio soundings at 13.00 UTC.

The same treatment is applied for the P2, a trend of 0.5°C being removed from the temperature data. In this flight leg the anomaly is off-centre, to the north-west (to leeward of the centre) and its intensity is slightly weaker (0.5°C) (Figure 7b).

In the flight leg P3 (1650 m of height), corresponding at this hour with the entrainment zone (Figure 2 and Figure 6), a large scale horizontal gradient (NW-SE) of temperature is observed by the aircraft (Figure 6b) and the radio sounding (Figure 5, from 1200m of height). A mean of the temperature field over the city is used to calculate perturbation created by the city at this height (Figure 7c). The temperature anomaly centred over the city is only visible in a little fraction of the flight leg (12.50-12.53 UTC in Figure 6b where the aircraft encounters a more turbulent zone between 42.5-43.65 of latitude in Figure 7c) suggesting that this level is still affected by the presence of the city by means of stronger updraft motions due to the enhanced sensible heat flux.

Note that in the numerical study of this case (Hidalgo *et al.,* 2008) the large scale horizontal gradient of temperature oriented in a NW-SE axis and the higher boundary layer over the city due to the updraft motions are confirmed and analysed.

5.2.3 Wind field analysis

The wind field measured by the aircraft flight allows to study the dynamics in the ABL, as these data provide a horizontal view of movements at three heights. The mean wind field provided by the flight leg at 350 m (Figure 8a) shows a weak south-easterly flow with a wind velocity smaller than 5 m s^{-1} over the urban area and even more to leeward of the city. The flight leg at 1650 m (Figure 8c) is submitted to a stronger westerly-north-westerly flow, which creates at 1100 m a transition layer between the two regions with a weak wind (Figure 8b).

At this hour, the perturbation created by the city in the mean wind field is still small compared to the magnitude of the wind, so this is not directly visible in the mean field. As for the potential temperature, the anomaly is calculated for each flight leg. The wind anomalies are computed excluding the zones with strong swerves of the aircraft. Furthermore, the synoptic trend for each leg, even if small, is linearly removed in order to focus on the perturbation due to the city. The result is averaged over 60 seconds in order to filter small scale turbulence. The aircraft speed being 72 m s^{-1} allows to take into account only the motions at scales larger than 4 km.

At the lowest levels (350 m, Figure 8d and 1100 m, Figure 8e) taking into account the UHI aforementioned a convergent flow towards the city centre is attended. This is true for P1 where clear convergence of 1-1.5 m s^{-1} is highlighted at 350 m with a horizontal extension of approximately 25 km (from 43.55 to 43.75 of latitude). The P2 is situated in the transition layer between the South-Easterly and North-westerly flows, due to weaker anomalies of temperature and wind, the result is more difficult to interpret in terms of convergence to the city centre at 1100 m of height. Even though the urban-breeze is driven by the SEB, vertical observations of the ABL structure are important to describe the horizontal transport in the lower layers.

At 1600 m (Figure 8f), a well marked divergence (the flow goes from the city centre to the outskirts) reaching 2 m s^{-1} is developed over the city. Its extension is about 30 km (from43.55 to 43.8 of latitude) off-centre to the North-West. Because the flight leg at 1650 m is in the thermal inversion, this shows that the wind perturbation due to the city extends to the entrainment zone.

5.3 Time-Evolution of the breeze

At the end of the afternoon, the ABL stops its vertical development and its height becomes stationary reaching a maximal height of 2200 m observed at 18.00 UTC in the city centre and 2000 m at Merville site (Figure 5). At this hour the horizontal gradient of temperature between the city centre and the rural site has vanished, and the city centre is now even cooler and moister in a layer from the surface to 400 m of height. Fresh air is transported by the south-Easterly flow from the rural zone situated upwind (Figure 9). This air mass is warmed over the city before reaching Merville.

The centre of the breeze is advected downstream of the city where the UHI is now located. A south-easterly flow in surface and a north-westerly flow at upper-levels is identified at the city centre in the RS of 18.00 UTC (Figure 10). This configuration indicates a convergent branch from the rural site (Merville, situated in the north-west) to the city at 250 m of height and a divergent branch from the city centre to the rural from 1500 m upwards. The urban-breeze circulation of 5-6 m s^{-1} intensity, probably enhanced by the continuous strong surface heating of the city, is then able to dominate the flow pattern at 18.00 UTC.

6. Conclusions

This study is focused on the IOP5 of the CAPITOUL experiment. Its main objective is to analyse an urban-breeze situation observed over the city of Toulouse (South-West of France) the 4th July, 2004. The meteorological conditions and the thermo-dynamical properties of the ABL were described using ground stations, wind profilers, radio soundings and aircraft data.

The synoptic situation of this day is favourable to the development of an urban-breeze circulation. This was a high insulated situation, the maximum net radiation being close to 650 W m^{-2}. The maximum of temperature in the city centre reached 34°C during this day. Moreover, a weak south-easterly flow in surface and a north-westerly flow at upper-levels created a region of a weak flow in the transition layer between the two regimes.

Typical features of urbanised areas described in the literature were found for this period. A nocturnal urban heat island of +5°C amplitude and a cool island of -1°C amplitude in the early morning were described in section 3. Due to reduced daytime evapotranspiration in the urban area, the sensible heat flux was during the afternoon approximately 250 W m^{-2} larger than in the countryside. This is the important feature of the Surface Energy Balance leading to an urban breeze.

This study shows the relative roles of the SEB components and the ABL structure for the development of the low-level airflow convergence towards the city. Even though the urban-breeze is driven by the SEB, surface measurements should go with vertical observations of the ABL structure to properly describe the horizontal transport in the lower layers.

The daytime +1 °C heat island centred in the city centre at 350 m of height and advected to leeward of the city at 1100 m of height is associated to the urban-breeze generation. The gradient of temperature starts at 12.00 UTC. The breeze observed by the aircraft between 12.30 to 15.20 UTC is composed of:

- Near surface convergence towards the city with an intensity of 1-2 m s^{-1} and with a horizontal extension in the axis SE-NW which is 2 to 3 times bigger than the size of the city.
- Divergent return in upper levels at the top of the ABL, reaching 2 m s^{-1} at 13.00 UTC.

The urban-breeze circulation grows in intensity during the afternoon and is able to dominate the flow pattern at 18.00 UTC.

This phenomenon has already been simulated by Lemonsu and Masson (2002) for Paris (France). The airborne measurements during the CAPITOUL campaign combined with the ground stations, wind profilers and radio soundings data, tends to demonstrate experimentally the existence of this kind of breeze in inland urbanised areas. This urban breeze episode was simulated with the MESONH model (Lafore *et al.,* 1998) and presented in a companion paper by Hidalgo *et al.* (2008).

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Station	LON	LAT	ALT	X	Fvc	AR	% Built	UCZ	H
UA									
27	1.4453	43.6036	144	0			100	2	20+30
21	1.4279	43.5962	138	1624	0,33	1,34	90	2	6
12	1.4443	43.5902	140	1493	0,23	2,03	80	2	6
07	1.4363	43.6083	139	894	0,54	0,65	80	3	6
RSUA									
01	1.4827	43.6522	143	6189	0,68	0,39	70	5	6
02	1.4122	43.6364	131	4524	0,82	0,19	0	6	6
04	1.4605	43.6224	145	2427	0,47	0,83	90	3	6
05	1.4389	43.6192	138	1810	0,45	0,9	60	3	6
08	1.3400	43.6050	180	8502	0,54	0,65	70	5	6
09	1.4757	43.6085	147	2514	0,61	0,51	70	3	6
10	1.4367	43.5888	138	1788	0,3	1,49	90		6
11	1.3886	43.5788	156	5342	0,58	0,58	50	5	6
13	1.4541	43.5791	150	2814	0,51	0,73	60	3	6
14	1.5165	43.5589	151	7595	0,53	0,67	60	5	6
15	1.4482	43.5577	260	5103	0,69	0,41	0	7	6
17	1.4762	43.5521	151	6244	0,6	0,52	70	5	6
19-20	1.3396	43.5326	167	11624	0,6	0,53	40	5	6
03	1.3964	43.6291	140	4860	0,6	0,52	60	5	6
NRSUA									
06	1.3498	43.6203	153	7928	0,79	0,24	20	6	6
16	1.4009	43.5493	148	7016	0,79	0,24	70	4	6
18	1.5077	43.5510	145	7712			90	4	3+4
22	1.3780	43.6230	151	5846			100	4	2,10
23	1.3667	43.5333	163	10067			80	6	2,10
24	1.3740	43.5747	158	6589			70	6	2,10
RA									
25	1.5049	43.5291	148	9570			10	6	2,10
26	1.5699	43.6286	207	10435			10	7	2,10

Table 1: *Surface network characteristics: station number, longitude (ºE), latitude (ºN), altitude over the sea level (m), distance from the central tower (m) (station 27, considered as the city centre reference), sky view factor, aspect ratio, percent of built cover in a radius of 500m, roughness class according to the Davenport (2000) classification, height of measure for the four classes defined (m) (urban area (UA), residential suburban area (RSUA), non-residential suburban area (NRSUA) and rural area respectively (RA)).*

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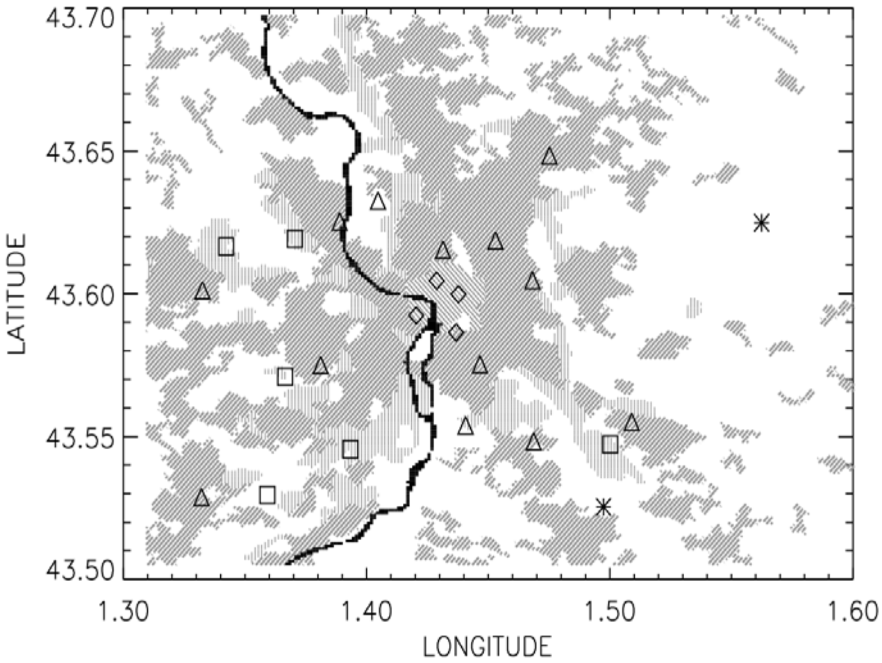
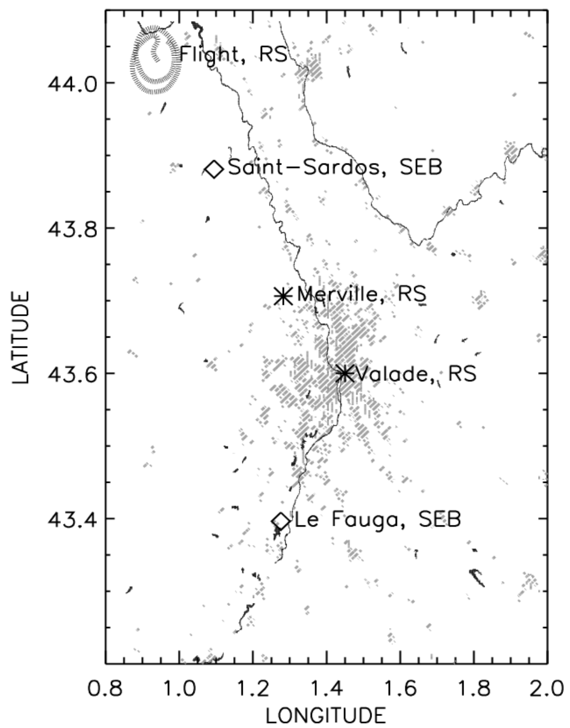


Figure 1a: *Surface network emplacement. The diamonds, triangles, squares and asterisks corresponds to urban, residential, non-residential and rural zones respectively described in Table 1. The covers are from the Corine Land Cover database: urban zone (grey (135º)), suburban zone (grey (45º)), commercial areas (grey (90º)) and the Garonne river (in black).*



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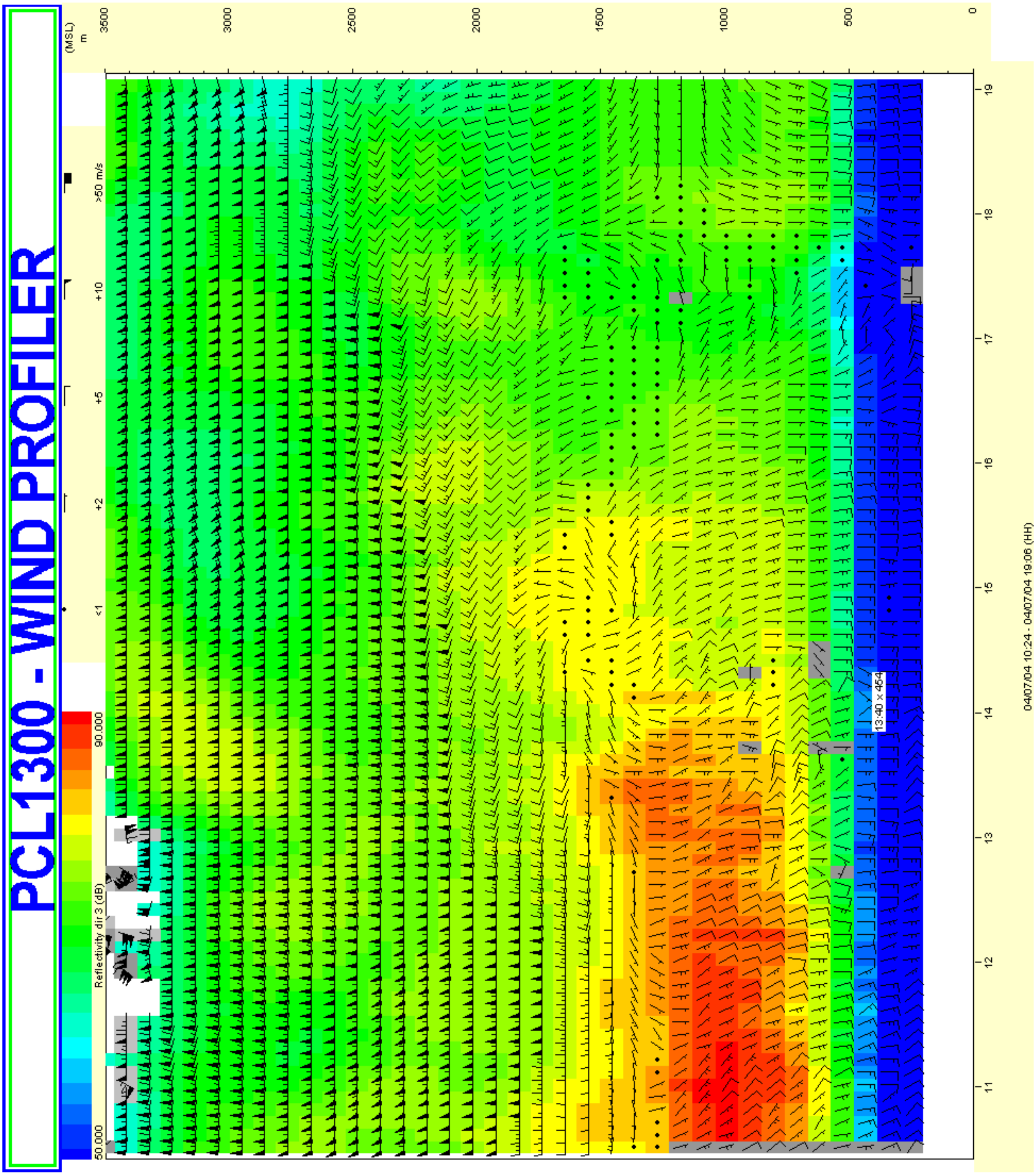

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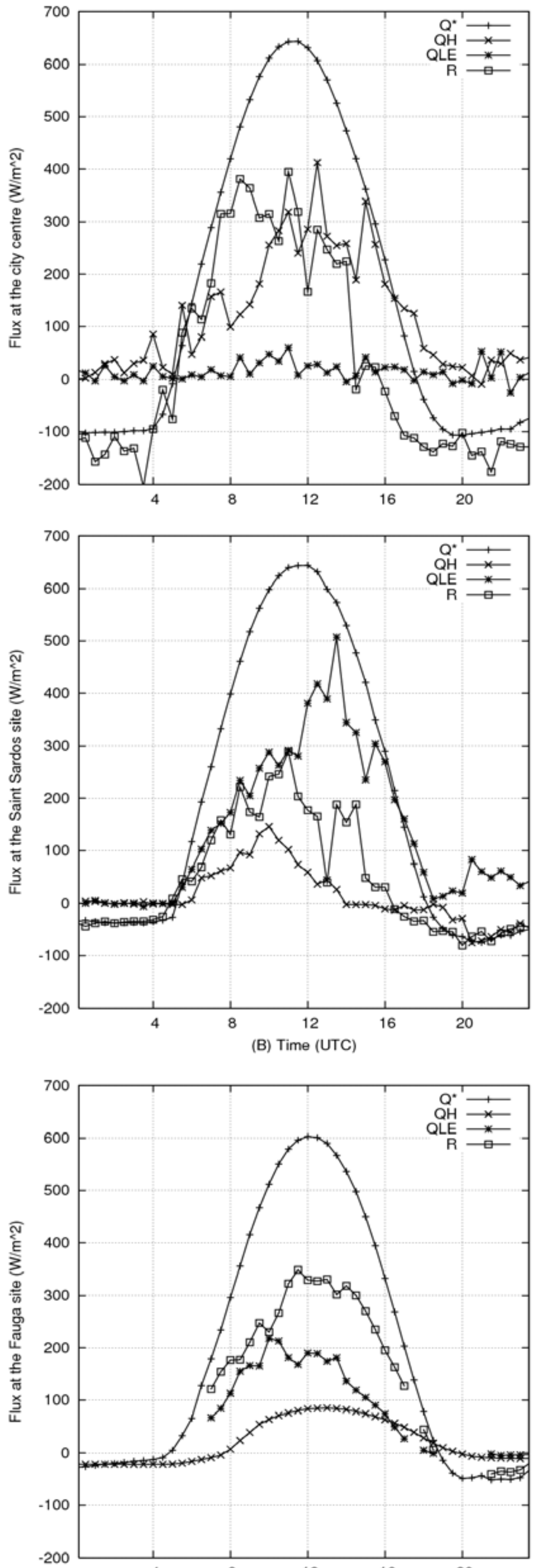

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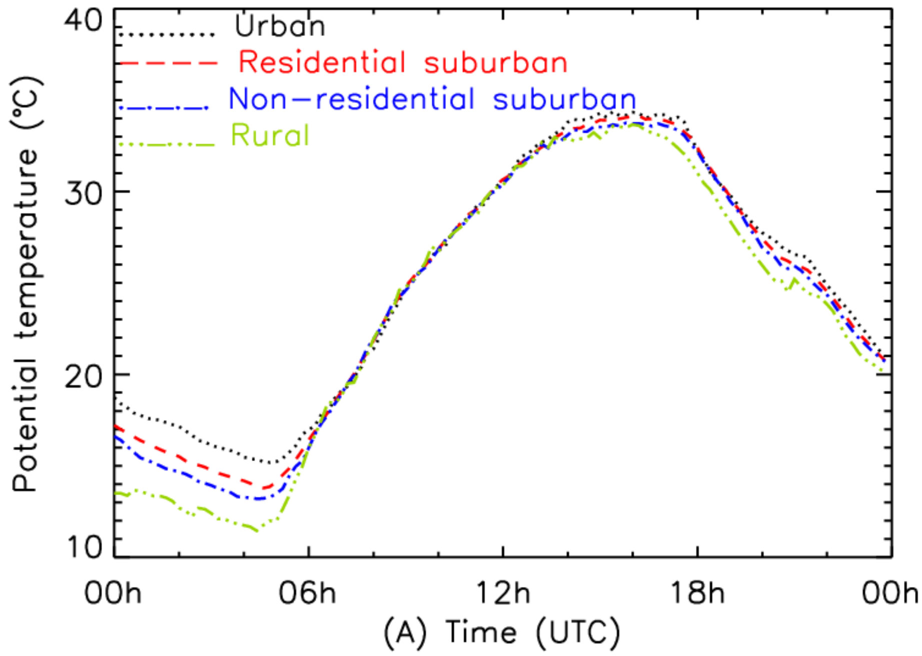

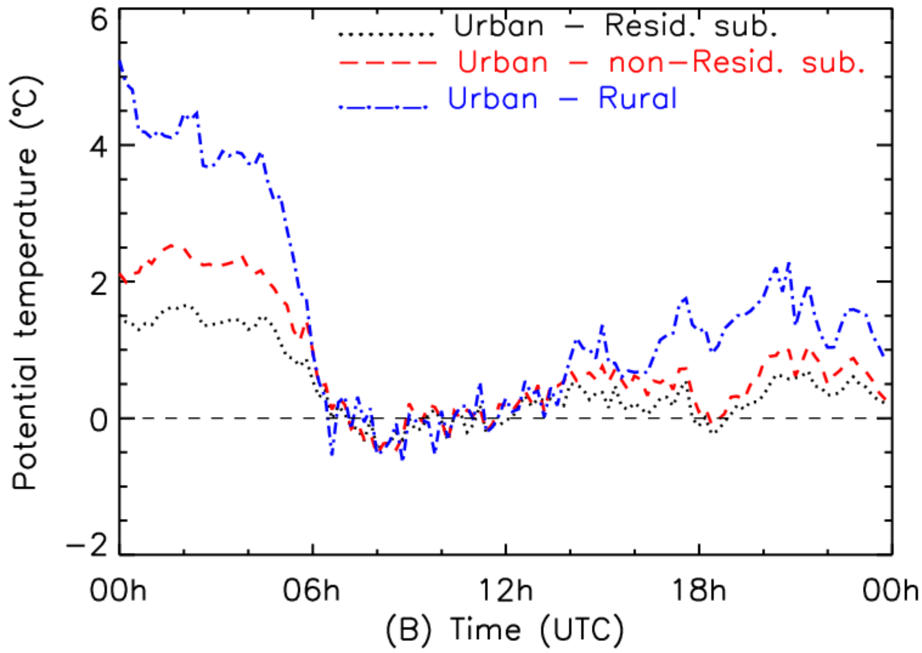

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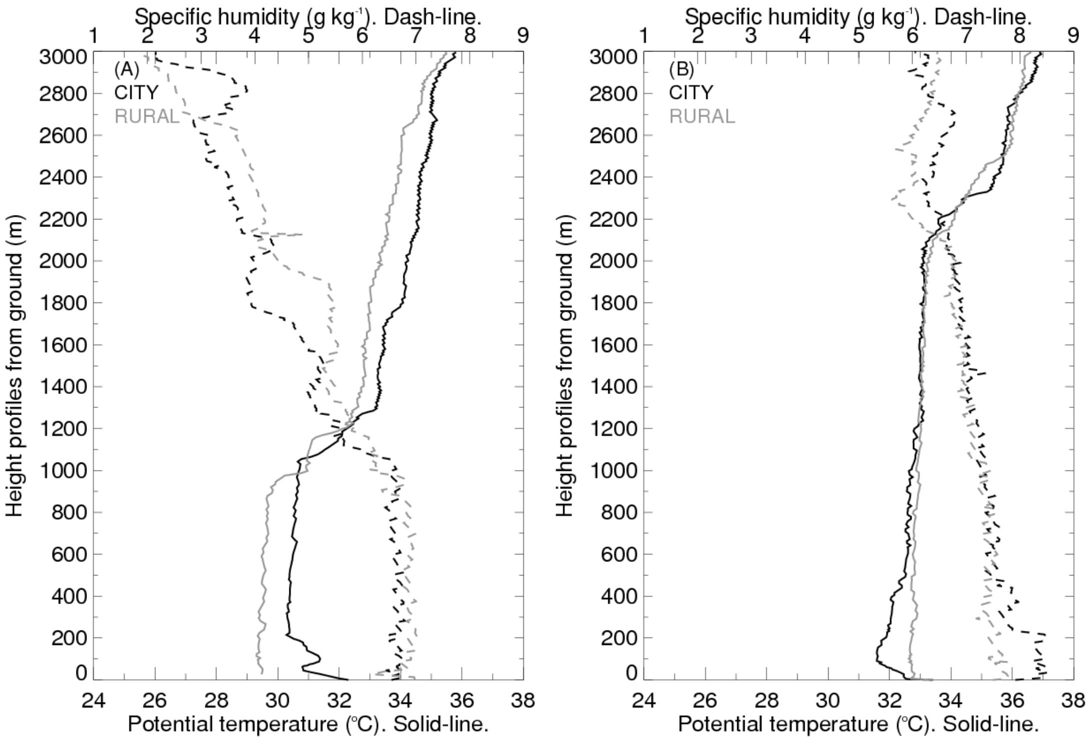

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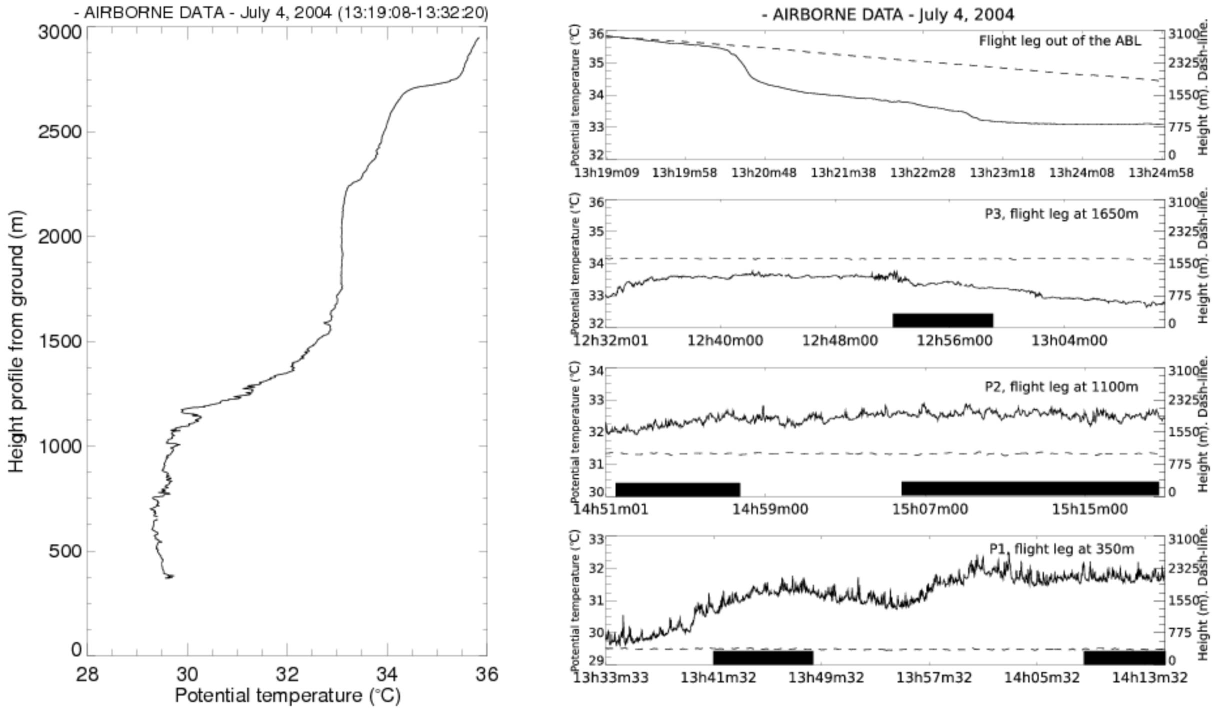

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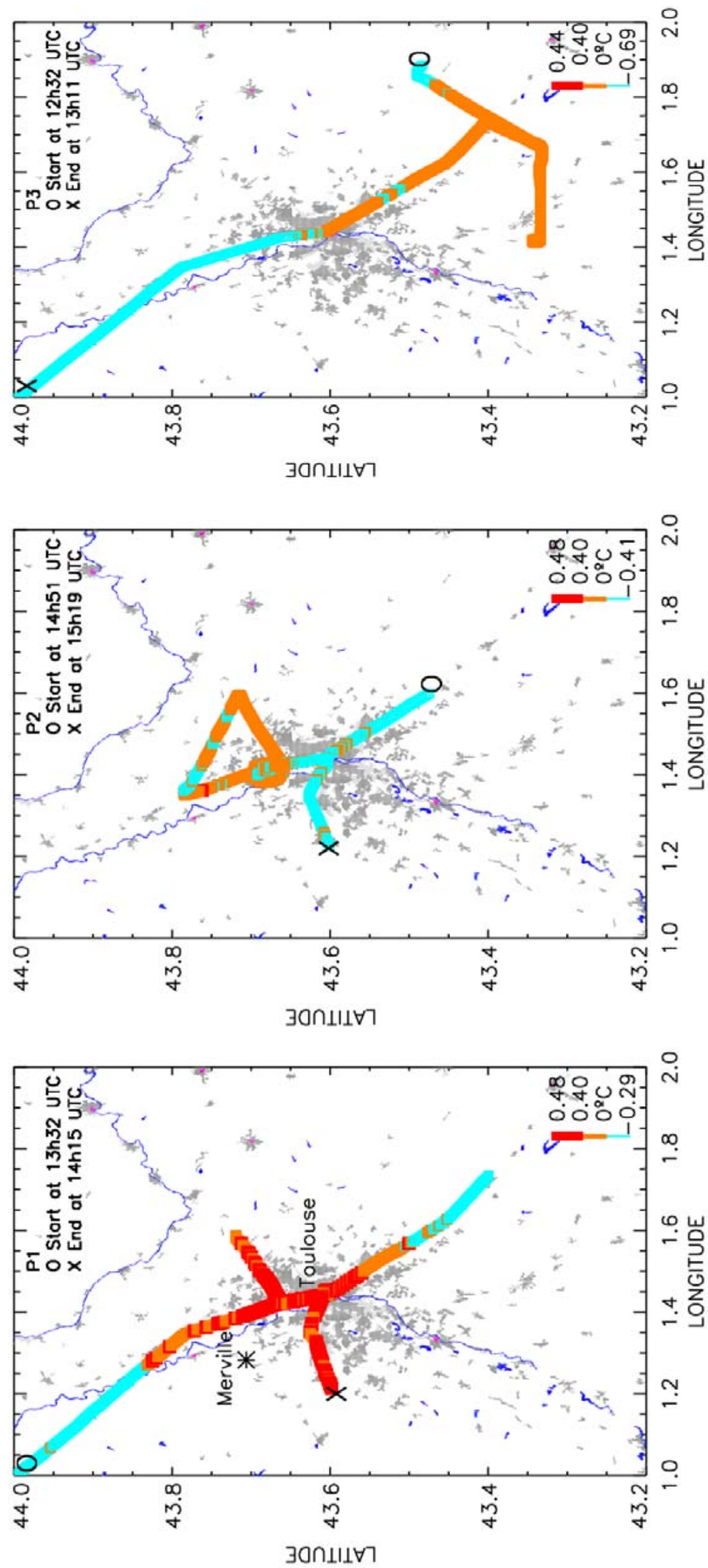

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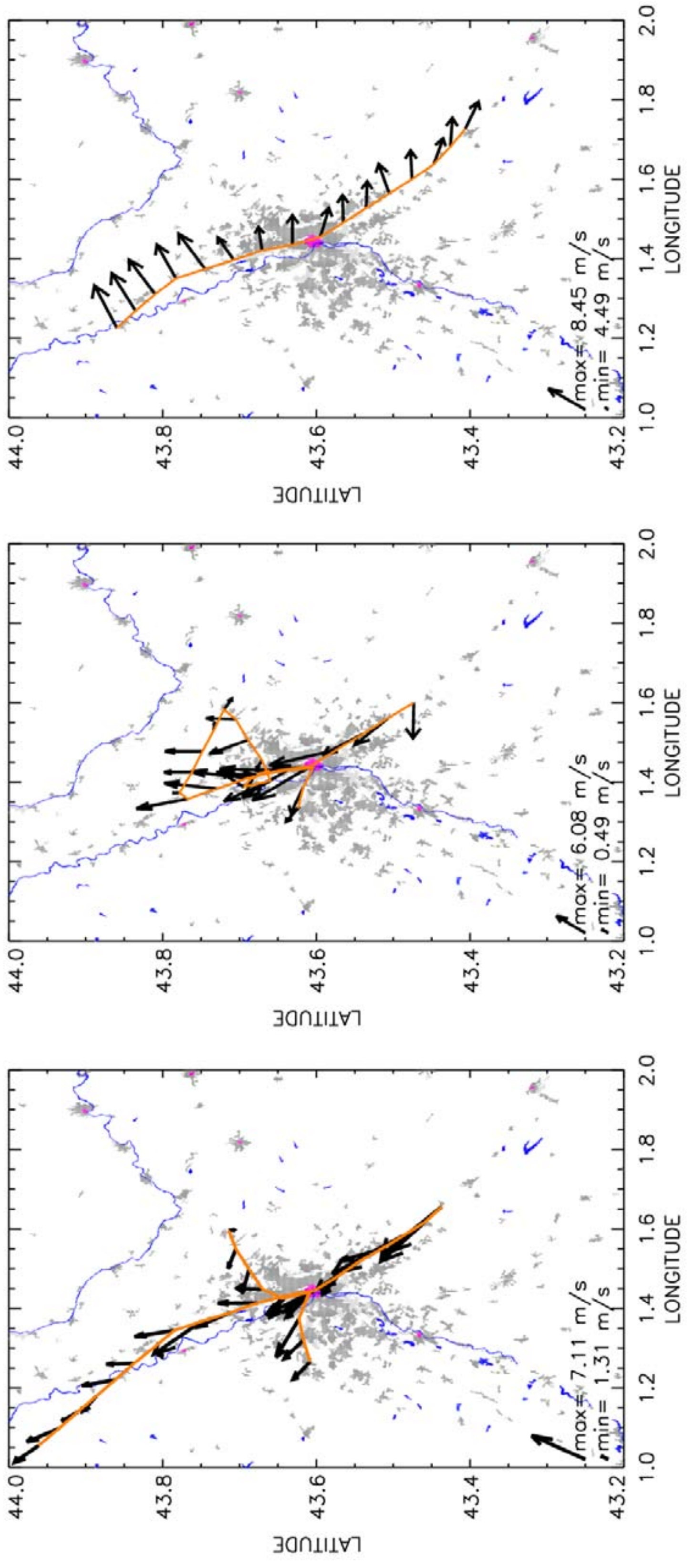

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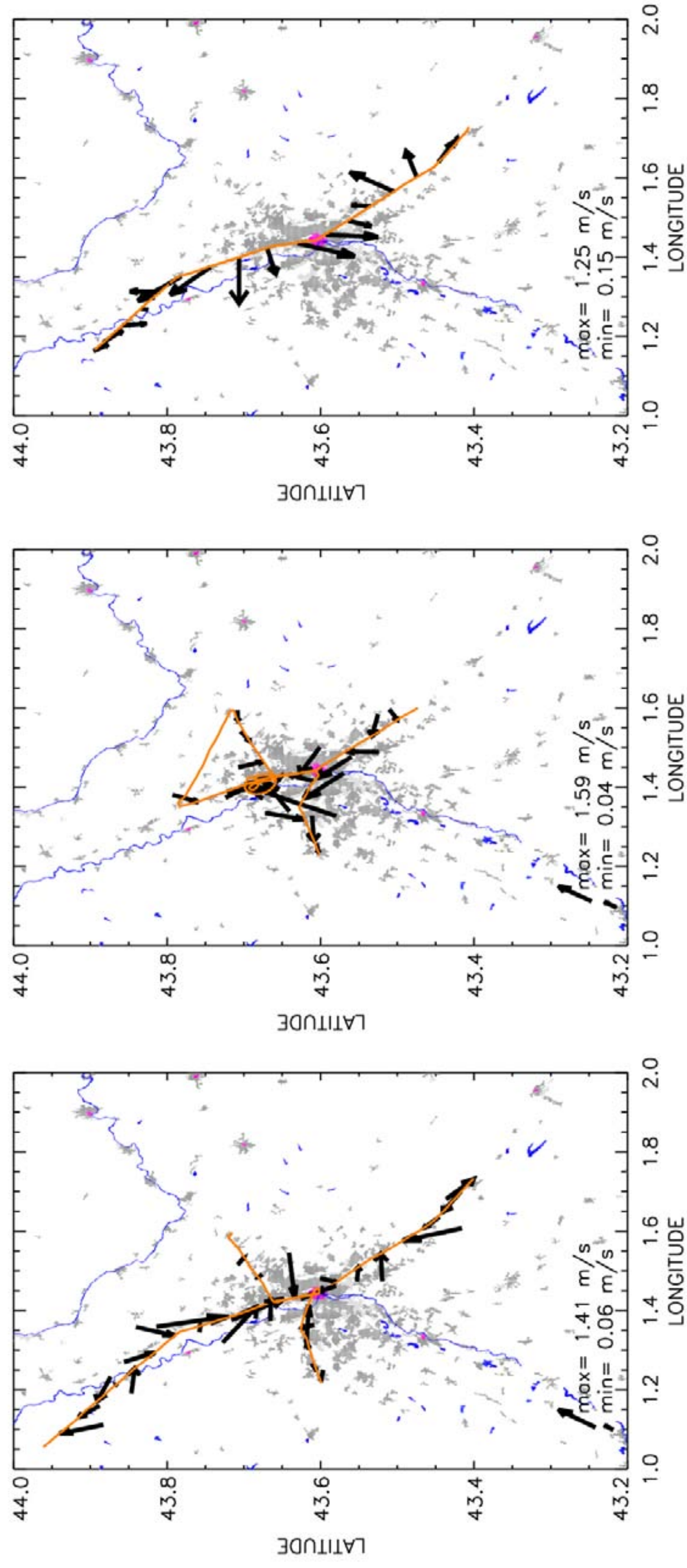

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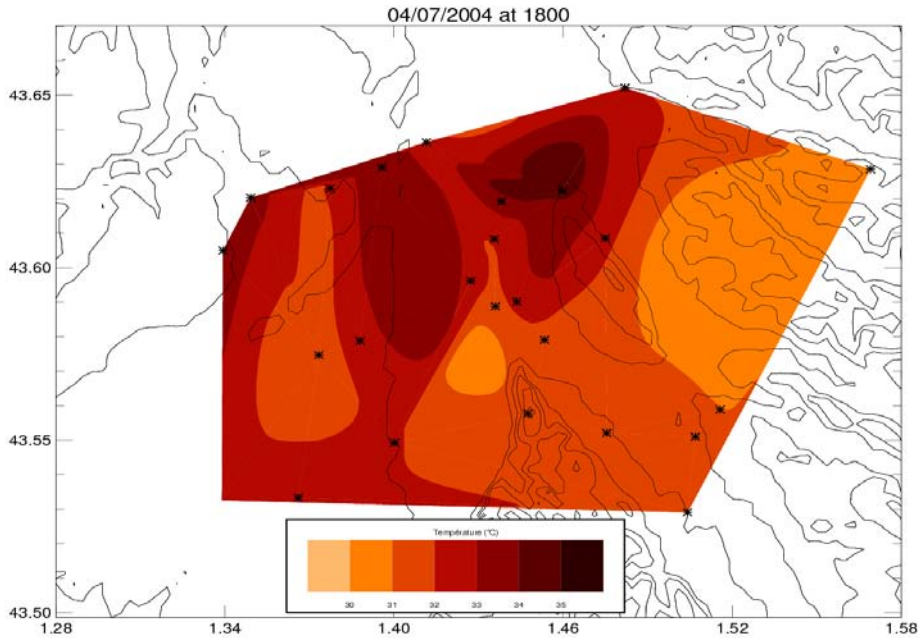

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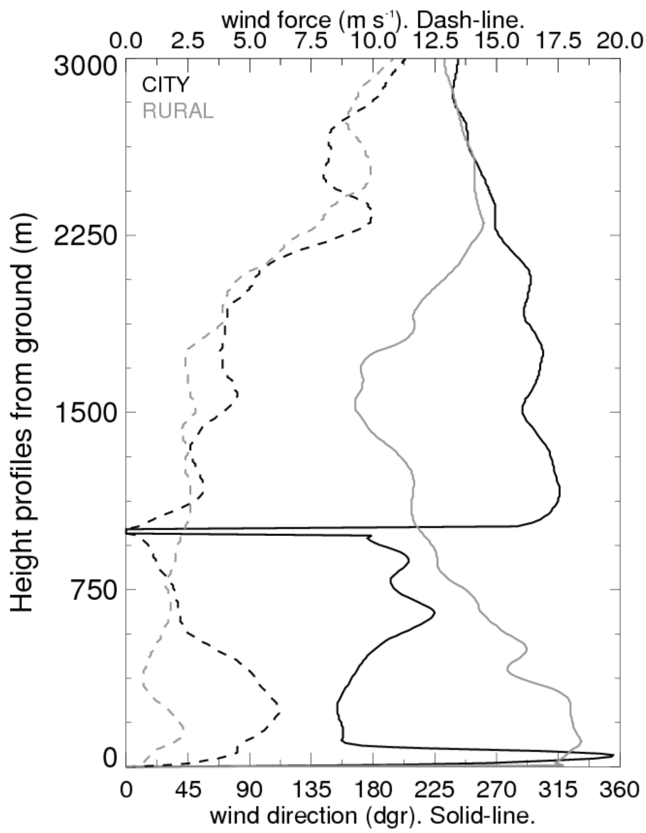

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Chapter 3

Modeling the Urban-Breeze Circulation

Modeling is a useful tool to study in depth the observed urban impacts on the atmospheric boundary layer. Numerical simulation of the atmospheric motions requires high performance computers-technology. The possibility of simulating the behaviour of the atmospheric boundary layer over complex terrain as urbanized surfaces with a suitable resolution using numerical techniques is possible thanks to:

- increase of computational simulation capabilities in terms of computational power and memory.
- the development of urban models representing surface-atmosphere exchanges, sensible and latent heat flux and net radiation.

Several mathematical models are used in all aspects of urban climate research where prediction is a major component, from episode forecasting to long term planning. These models have been classified into CFD (Computational Fluid Dynamics) or mesoscale models.

- The CFD models are generally used for local forecasting/simulation of weather and air pollution (section 1.2.4). These simulations explicitly resolve individual buildings and are limited by computational requirements to domains of a few kilometers. The fundamental emphasis of CFD simulations lies in the physical difficulties of modeling the effects of turbulence. Other major issues are the accuracy in the spatial discrimination of complex urban geometries using a three dimensional mesh made up of arbitrary hexahedrons. Accuracy depends on the availability of the resources in order to perform the calculations on finer mesh. CFD models generally solve the basic mass, momentum and energy transfers equations.
- Mesoscale models use prognostic equations for the calculation of atmospheric wind, temperature,

moisture content, etc. It can represent 3D fields including terrain effects. Mesoscale models and other larger scale models do not explicitly treat buildings, but include the effect of buildings using different strategies classified into five main categories by Masson (2006): models that fit to observations, modified vegetation schemes with or without drag terms in the canopy and new urban canopy schemes that present horizontal and vertical surfaces, again with or without drag approach. Nested simulations up to mesoscale with a suitable model hierarchy allows the description of interactions between larger scale meteorological phenomena and urban scale processes.

In this study the model MésoNH (Lafore *et al.,* 1998) is used to reproduce the urban-breeze episode observed during the CAPITOUL campaign. MesoNH is the non-hydrostatic mesoscale atmospheric model of the French research community. It has been jointly developed by the Laboratoire d'Aerologie and by CNRM-GAME. The model is intended to be applicable to all scales ranging from large (synoptic) scales to small (large eddy) scales. For this study the model is coupled with the urban surface scheme TEB (Town Energy Balance; Masson, 2000) to simulate the urbanised areas and with the ISBA (Interaction Soil Biosphere Atmosphere; Noilhan, 1989) to simulate natural covers.

The strategy used to display the impact of the urbanisation on the atmospheric boundary layer is to perform two simulations at high horizontal resolution (250 m): A realistic situation where MesoNH is coupled with TEB and ISBA and a second one where the urbanized areas have been removed (the scheme ISBA replaces the scheme TEB in each grid box, with the characteristics of the most common rural land use category in the zone). The urban-breeze circulation is revealed by comparison of the two simulations fields.

The Chapter is presented in article form. This article has been submitted to the same thematic number of “Meteorology and Atmospheric Physics” (Springer) cited on Chapter 2, as a second part of the experimental study of the urban-breeze circulation. At the time this manuscript is written, the article is waiting the acceptance after revision and resubmission.

Urban-Breeze Circulation during the CAPITOUL Experiment:

Numerical Simulations

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Abstract: In this study we present a numerical simulation of the urban-breeze circulation observed in Toulouse, South-West of France, during the Intensive Observation Period number 5 (IOP5, 3rd and 4th July 2004) of the CAPITOUL experiment (Feb. 2004 to Feb. 2005). The numerical simulation is performed with the non-hydrostatic atmospheric model MesoNH (Lafore *et al.*, 1998) coupled with the urban surface scheme TEB (Masson, 2000). Four two-way, grid-nested models with horizontal grid resolution of 12 km, 3 km, 1 km and 0.25 km are used.

The diurnal cycle of temperature, the nocturnal heat island and the early morning cool island are reproduced by the model. For the urban-breeze period, between 12.00 UTC to 18.00 UTC, the heat island structure and the simulated turbulent fluxes are discussed based on the observed surface energy balance and urban canopy temperature. The numerical simulations confirm the presence of a convergent circulation at the surface towards the city centre and a divergent counter-current 1500 m above the ground. The intensity of the urban-breeze circulation is of the order of 1.5 m s^{-1} and its extension, in the mean wind axis, is two times the diameter of the city.

The dynamical perturbation on the ABL due to the roughness of the city is only significant up to 50m of height, the urban breeze circulation being caused by the pressure gradient due to the UHI-induced thermal effects. An evaluation of the improvement on the ABL thermodynamics representation when going down to 250 m of horizontal resolution instead of 1 km is also presented.

Keywords: Urban-breeze, heat island, CAPITOUL experiment, numerical simulation, MesoNH

1. Introduction

The urban-breeze is a mesoscale phenomenon (Oke, 2005) specific to urbanised environments. The different response of the countryside and the city centre surface to the diurnal cycle of heating and cooling creates an horizontal gradient of temperature called Urban Heat Island (UHI; Oke, 1987). The UHI, generates a differential temperature advection from rural to city centre and is the source of the urban-breeze circulation.

The urban-breeze is characterized by a surface convergent flow from the countryside to the city centre and a divergent flow at the top of the Atmospheric Boundary Layer (ABL). Urban-breeze can steer pollution from industrial areas and trap it in the ABL (Sharan *et al.*, 2000). To ameliorate pollution peaks forecast and to evaluate air quality policy in the cities it is important to understand this type of circulation. However, its dynamics and its structure in a hinterland city is currently little known.

The urban-breeze circulation observed by Hidalgo *et al*. (2008) the 4th July 2004 during the IOP5 (Intensive Observation Period number 5, 3rd and 4th July 2004) of the CAPITOUL campaign (Feb. 2004 to Feb. 2005; Masson *et al*., 2008), is studied here in detail using numerical simulation techniques. During this experiment, Toulouse was under a very stable high-pressure summer system with a well developed Urban Boundary Layer (UBL). The large-scale wind was characterized by a weak velocity blowing from the south-east near the surface and from the north-west at upper-levels. Under such circumstances, transport within the mixed layer is dominated by local circulations. During the IOP5, near surface convergence towards the city and divergent return in upper levels at the top of the ABL are observed during daytime. The intensity is of 1-2 m s^{-1} and the horizontal extension in the axis SE-NW is 2 to 3 times bigger than the size of the city.

High resolution numerical simulations are used to study the 3-D mesoscale urban effects difficult to observe with an observational deployment. Masson (2006) classifies the models which describe the perturbation created by the urban surfaces in the ABL structure in three main categories according to their degree of physics description: empirical models, modified vegetation schemes and urban canopy schemes (single- or multi-layer models). Urban-breeze circulation shall be studied at the meso-scale (city plus its surroundings) (Oke, 2005). Single-layer urban schemes are appropriate to describe the influence of cities, from regional to mesoscale and urban scale (Masson, 2006). This technique was already used by Lemonsu and Masson (2002) to study the urban-breeze in Paris area using the MesoNH atmospheric model (Lafore, 1998) coupled with the Town Energy Balance (TEB) urban scheme (Masson, 2000).

We present here two numerical simulations performed with the same atmospheric and urban surface models as used by Lemonsu: a realistic situation (URB) where urbanised areas are resolved and a second one (RUR) where the urbanized areas has been removed. These numerical simulations are described here and evaluated using the experimental dataset from the IOP5.

An observed nocturnal +5°C UHI during the 3rd to 4th July 2004, a daytime gradient of surface sensible heat flux between the urban and rural zones of 200 W m^{-2} creating a daytime UHI with +1°C of intensity and a south-easterly flow in surface changing to a north-westerly flow in upper levels are the main characteristics of this day. The horizontal wind field, the surface parameters and the vertical evolution of the ABL are analysed. A comparison between the two numerical simulations (URB and RUR) allows isolation of the effects of the UHI on the ABL properties and in particular on the horizontal and vertical wind fields.

2. Numerical simulations description

Two numerical simulations were performed using the Méso-NH atmospheric model described in Lafore *et al.* (1998). A realistic situation (URB) where MesoNH is coupled with the surface scheme TEB (Town Energy Balance; Masson, 2000) to simulate the urbanised areas and with the ISBA (Interaction Soil Biosphere Atmosphere; Noilhan, 1989) to simulate natural covers. In the second one (RUR), the urbanized areas have been removed (the scheme ISBA replaces the scheme TEB in each grid box, with the characteristics of the most common rural land use category in the zone) to display the impact of the urbanisation on the airflow within the mixing layer by comparison with URB .

Spatial coverage and resolution: For both simulations (URB and RUR), four two-way, grid-nested models are used in order to obtain a high horizontal resolution over the city of Toulouse. The horizontal grid resolution of these models are 12 km (M1), 3 km (M2), 1 km (M3) and 0.25 km (M4) (Figure 1a, b and c). The high resolution in the last domain (250 m) allows the explicit representation of the largest turbulent eddies above the canopy for daytime urban boundary layer. The Appendix explains the interest to explicitly represent a part of the Boundary Layer turbulence for a better simulation of the spatial structure (including on the vertical) of the UHI for a city of the size of Toulouse. The horizontal domains are 1800 x 1800 km, 300 x 300 km, 60 x 60 km and 30 x 30 km respectively.

The vertical coordinate is composed of 50 levels. Stretching is used to obtain a fine description of the first atmospheric levels. The mesh length in z-direction near the ground is 12 m and 400 m near the top of the model, with a 20% constant stretching. Fifteen levels are located in the first 1000 m to finely resolve boundary-layer properties. The first atmospheric level is situated 6 m over the natural cover or over the top canyon in the case of urbanized areas.

Temporal coverage and resolution: This study is focused on the IOP 5 (3rd and 4th July 2004) of the CAPITOUL experiment. The whole period (48 hours) is simulated in a single run. The simulation starts at 00.00 UTC the 3rd July with M1 and M2 grid-nested models. The first 18 h of the simulation are considered as an initialization period (spin-up). This is necessary in order to represent the heat storage in the building and roads during the day (3rd July) that will be responsible of the UHI during the following night. The next 30 h are simulated with the four grid nested models M1, M2, M3 and M4 (18.00 UTC the 3rd July to 24.00 UTC the 4th July).

The temporal discretization is carried out by a leapfrog scheme and an Asselin's filter (Asselin, 1972). The time step used for the four grid-nested models run are: 15, 3.75, 1.25 and 0.31 seconds for M1, M2, M3 and M4 respectively.

Initial and boundary conditions: The initial and boundary conditions of the first domain (M1) are defined every 6 hours using the ARPEGE global circulation model analyses (Courtier *et al.*, 1991). For the other three models (M2, M3 and M4) the two-way grid-nesting method is used. Information between two successive models is exchanged at every time step (Stein *et al.*, 2000). The open lateral boundary condition is given by the Sommerfield equation for the normal component of the velocity proposed by Carpenter (1982).

Parametrizations schemes: The radiation scheme used is that of the European Center for Medium-Range Weather Forecasts (ECMWF) scheme (Morcrette, 1991) and the ICE3 microphysical parameterization (Pinty and Jabouille, 1998). For the first three models, the turbulence scheme (Cuxart et al 2000) is based on a prognostic Turbulent Energy Equation and use a mixing length computed using the Bougeault (1989) scheme. For the last model M4, the turbulence scheme (also Cuxart *et al.*, 2000) now solves the turbulent fluxes in all 3 dimensions.

Surface schemes. Characterization of Toulouse's city centre: In the simulation URB, the surface schemes TEB and ISBA, are coupled to the MesoNH model as explained in Pigeon *et al.* (2006). The TEB urban scheme is a *single-layer* model (the exchanges occur only at the top of the canyon and roof (Masson, 2000). TEB parameterizes town-atmosphere thermodynamic interactions using a realistic parameterization of the urban 3D geometry based on the "urban canyon" geometric model (Oke, 1987). For natural covers, ISBA parameterizes the exchanges between the atmosphere and the surface. In the simulation RUR, only ISBA scheme is activated to parametrize the surface.

For this study no Toulouse-specific database (anthropogenic emissions, land cover map, geometric parameters of the streets or thermal properties of building and road materials) was available. To initialise both surface schemes, the land cover for all models is described by the 1 km of horizontal resolution Ecoclimap surface parameters database (Masson *et al.*, 2003). The land cover of Ecoclimaps uses the CORINE classification (Corine, 2000). Corine land-cover provides 44 classes for Europe of which 11 are urban classes.

3. Regional Forcing Validation

The quality of simulated fields at the local scale is linked to a good representation of the simulated regional forcing. The large-scale wind field, the potential temperature and the water vapour mixed ratio are analysed below using the results of the model at 1 km and 0.25 km of resolution (URB(M3) and URB(M4)). The simulation's quality is evaluated by comparison with experimental observations of the IOP5 from the CAPITOUL campaign.

3.1 Observational Network

The IOP5 provides boundary layer characteristics for both urban and rural environments. The MesoNH performance is tested using data from the surface network of 21 temperature and relative humidity mini-stations. A 30 m hydraulic tower was located on the roof of a building (situated 20 m above the ground) and two flux stations were situated at 15 km south-west (Fauga, situated in a grassland area) and at 40 km north-west of Toulouse (Saint-Sardos, situated in a irrigated maize crop land). The boundary layer instrumentation consisted in: Ultra-High Frequency radar (UHF) situated in the city centre, radio soundings launched from the city and from rural site (~ 15 km NW of the city) and the Meteo-France instrumented aircraft *Piper Aztec.* The whole experimental network for this IOP is described in detail by Hidalgo *et al.* (2008, their Figure 1).

3.2 Horizontal wind field

The aircraft *Piper Aztec* flew legs on the afternoon of the 4th July between 12.08 and 15.26 UTC at altitudes of 350, 1100 and 1650 m. The mean wind field provided at 350 m (Hidalgo *et al.,* 2008a; their Figure 8a), shows a weak south-easterly flow with a wind velocity weaker than 5 m s^{-1} in the urban area and even weaker leeward to the city. The flight leg at 1650 m (Hidalgo *et al.,* 2008a; their Figure 8c), indicates the existence of a stronger westerly-north-westerly flow which creates a transition layer between the two regions with weak wind at 1100 m (Hidalgo *et al.,* 2008a; their Figure 8b).

Figure 2 shows the horizontal wind modelled by URB(M3) (1 km of horizontal resolution, 60 x 60 km of spatial coverage). Outputs are averaged for the same period of the flight (12.30 to 15.30 UTC) in order to capture the mean horizontal wind field in the region. It appears that at low levels (Figure 2a), Toulouse is under the influence of a weak south-easterly wind flux with intensities varying from 2 to 3.5 m s^{-1}. There is a terrain-induced deflection of the mean flow by the little hills situated in the SE of the analysis area. The airflow is slowed to 1.5 m s^{-1} downwind of the city. At 1650 m (Figure 2c), the influence of the city is not directly visible in the mean wind, only the orography situated in the south and east clearly modifies its direction and intensity. MesoNH succeeds to simulate the sheared wind profile present during this day, large-scale wind is in agreement with flight observations for the three flight levels (350, 1100 and 1650 m).

3.3 Potential temperature and water vapour mixing ratio

The time series of potential temperature and moisture observed by the *Piper Aztec* and those modelled by MesoNH (URB(M4) and URB(M3) when the aircraft goes out of the M4 domain) are shown in Figure 3. Potential temperature and vapour mixing ratio are reproduced by the model for the flight legs P1 and P2 (350 and 1100 m respectively). These flight legs are situated inside of the convective mixed layer at this hour (Hidalgo *et al.* 2008). Biases between the observations and the simulation for these time series are lower than 1°C and 1 g kg^{-1} respectively (Figure 3).

For the flight leg P3 (situated at this hour at the top of the entrainment zone, (Hidalgo *et al.,* 2008), potential temperature is underestimated by about 2 – 2.5°C and moisture is overestimated by 2-3 g kg^{-1} at 1650 m of height. This divergence is due to a faster vertical development of the modelled ABL during the morning. At 13.00 UTC the modelled ABL is 200-250 m higher than the one observed by the radio sounding. This bias decreases during the afternoon and at the end of the day (18.00 UTC) the ABL has a height 100 m lower than the observed one and the difference on potential temperature is then 0.5°C at 2000 m.

4. Temporal and spatial relations between thermodynamics fields and surface parameters

4.1 Surface Energy Balance (SEB)

During this IOP, three sites were equipped to document the SEB of Toulouse and its surroundings. One located in the city centre, the other two in rural areas north-west and south-west of Toulouse (Saint

Sardos and Fauga respectively). A detailed analysis of the observed turbulent fluxes densities during this day is described by Hidalgo *et al.* (2008).

The energy balance at the top of the street canyon is described by Oke (1988) as:

$$Q^* + Q_F = Q_{LE} + Q_H + \Delta Q_S + \Delta Q_A$$

The flux densities of net all-wave radiation (Q^*), sensible heat (Q_H) and latent heat (Q_{LE}) are measured directly (calculated with the eddy-covariance method (Pigeon *et al.,* 2007)). These three components of the SEB are compared with those simulated by MesoNH.

The anthropogenic heat flux (Q_F) estimated from inventories by (Pigeon *et al.,* 2007), the below roof advection divergence (ΔQ_A) and the storage heat flux (ΔQ_S) were analysed by Hidalgo *et al.* (2008a).

The shape of the daily cycle of net all-wave radiation Q^* is simulated by the model for both environments (Figure 4). In the city centre, there are small biases in the simulation of the negative nocturnal values (-100 W m^{-2} observed at 00.00-04.00 UTC and at 20.00-24.00 UTC, -70 W m^{-2} modelled by MesoNH). It is linked to the underestimation of the nocturnal sensible (Q_H) and latent (Q_{LE}) heat flux densities. The latent heat flux Q_{LE} is overestimated in the city during daytime by about 50-100 W m^{-2} and in the rural site 50-200 W m^{-2} from daybreak to noon.

The model is able to accurately simulate the diurnal sensible heat flux density for urban and rural zones. The sign of Q_H determines the stability of the near-surface air layers. During the period of the breeze (12.00 to 18.00 UTC), the sensible heat in the rural sites have small values (0-100 W m^{-2}) whereas the city centre have, during the same period, strong Q_H positive values (350 W m^{-2}). This difference in the distribution of the surface energy between the urbanised and rural zones is the key to the breeze generation. Upward motions are generated in the urban zone, favouring a convective circulation over the city.

4.2 Night-time and daytime surface heat and humidity islands

The ability of the model to reproduce the variability of the horizontal thermodynamics fields over Toulouse area, is tested here by analysing the 2 m air potential temperature and specific humidity fields from the URB(M4) simulation.

The urban heat island (UHI), is a phenomenon with a horizontal extension, under low large scale winds, comparable to the whole city extension. The measurement at a ground station is representative only of a small area around the station (local scale). To obtain a good representation of the UHI over Toulouse, the data from the network of 21 temperature and relative humidity stations situated in the city centre and suburban areas of Toulouse, are averaged according to four classes (urban area, residential suburban area, non-residential suburban area and rural area; Hidalgo *et al.,* 2008). The output values of the parameters from the model URB(M4) have been extracted at grid points corresponding to the location of the stations. Then, as for the observations, simulation outputs have been averaged according to the four classes defined previously.

Figure 5a compares the shape of the diurnal cycle for the potential temperature simulated and observed during CAPITOUL. As observed, the difference of temperature between daytime and night-time increases from the city centre to the rural zone. However the high thermal amplitude observed during this day (23°C), is slightly underestimated by the model (21°C).

During the night from 3[rd] to 4[th] July, the rapid cooling in the countryside and the observed upward-directed turbulent flux densities caused by the release of the energy stored in the urban materials, results in an observed nocturnal UHI with an intensity between +3 and +5°C (Figure 5b). In the rural zone, the model overestimates the temperature by 2.5°C at 00.00 UTC (Figure 5c). The radiative cooling simulated during the night, has the correct trend and at 05.30 UTC when the temperature reaches the minimum, its overestimation is weak (1.25°C). In the urban zone, the temperature at 00.00 UTC is 1°C warmer to the one observed. The overestimation rises to 1.5°C at 05.30 UTC. Despite the bias between the temperatures simulated for the four zones, the gradient of temperature results in a simulated nocturnal UHI (Urban – Rural zone) with a correct mean intensity of 4°C for both, observations and model. (Figure 5b).

From the daybreak until noon, the model achieves its best performance, simulating temperatures with a bias lower than 0.5°C. There is a clear trend in the bias to underestimate the temperature as the day goes by (Figure 5c). MesoNH succeeds in simulate the time-shift of the atmospheric heating in the city centre in comparison with the rural zones. The urban cool island of 1°C of intensity observed between 06.00 to 10.00 UTC is well simulated in duration but its intensity is slightly overestimated especially at 8.00 UTC (Figure 5b).

For the period of the breeze (12.00 to 18.00 UTC), the bias remains lower than 1.5°C (Figure 5c) being the residential and non-residential suburban zones the best areas simulated. The daytime heat island observed during this period (1 to 1.5°C of intensity) is simulated for the UHI (Urban – Rural zone). This daytime UHI is an important element for the generation and persistence of the urban-breeze circulation observed this day. The gradient is inverted for the UHI (Urban- residential zone) and UHI (Urban- non-residential zone) due to a underestimation on the potential temperature in surface for the city.

The same strategy is used to obtain the specific humidity at 2 m for the four representatives zones (urban, residential suburban, non-residential suburban and rural). The observed specific humidity maintains a constant value of 7 g kg^{-1} until late in the afternoon (Figure 6a). Characteristic features of this day are: the gradient of humidity between the city and the rural zone from 12.00 to 18.00 UTC (Figure 6b) and the maximum of 9.5 g kg^{-1} reached after 19.00 UTC when a new air mass advected with the large scale westerly wind is incorporated to the ABL (Figure 6a).

MesoNH simulates the observed humidity from 00.00 to 12.00 UTC with a bias lower than 0.5 g kg^{-1} (Figure 6c). Sources of humidity are weaker in urbanised zones than in rural zones, producing a dry moisture island during daytime. The days preceding the experiment corresponds to a cloudy period with no rain. As a consequence, there is no water available for evaporation over urban surfaces while the soil is still sufficiently moist to enable evapotranspiration by the vegetation in rural zones. The increase of humidity near surface in late afternoon is overestimated by MesoNH in 2.5 g kg^{-1}, because of the overestimated latent heat flux during the afternoon.

In general terms TEB is able to simulate the surface temperature and humidity, the bias between observed and simulated temperatures remains low in spite of the fact that no specific database were used to describe the thermal properties of the surface of Toulouse.

5. Vertical Boundary Layer Development. Urban-breeze circulation

Here the features of the ABL development in terms of wind field, temperature profile and wind anomaly with respect to the mean wind field are analysed.

5.1. Urban dynamical impact in the morning

The turbulence in the ABL can be produced by buoyant convective processes and mechanical processes. Modified artificial surfaces have a different response to the diurnal cycle of heating and cooling. As seen in section 4, the result is a modified SEB and a horizontal gradient in air temperature called urban heat island. The atmosphere over hot surfaces is more unstable and vertical motions are favoured (i.e. thermals of warm air rising). On the other hand, the characteristic roughness of the urbanized zones modifies the mean wind flow in its way through the city. The mean kinetic energy is transformed in Turbulent Kinetic Energy (TKE) and results in increased turbulent motions. A boundary with strong wind shear is created at the top of the canopy. This mechanical perturbation of the ABL by the urban surface is analyzed hereafter by comparing the realistic case URB(M3) and the simulation RUR(M3) were the urbanized areas have been removed.

The UHI between urban and rural zones is minimal for the period 09.30 to 11.30 UTC (Figure 5b) and we assume that only mechanical processes play a major role in the perturbation of the wind field. The deceleration on the wind due to the roughness of the city is of 1.5 m s^{-1} at 6 m over the urbanised area. This drag decreases rapidly with height. The intensity halves at 25 m and is close to zero at 110 m of height (not shown).

5.2 Perturbation on potential temperature in the ABL

The anomaly on the potential temperature of the ABL created by the city, observed during the aircraft flight (12.30 to 15.30 UTC) is analysed in Hidalgo *et al.* (2008). The flight legs situated in the convective mixed layer (350 m and 1100 m) shows a heat island of 1°C and a 0.5°C intensity respectively. The UHI is slightly advected off-centre to the north-west (leeward to the mean flow). The aircraft crossed the entrainment zone top to the free atmosphere at 1650 m (Hidalgo *et al.,* 2008a; their Figure 7a to c).

Figure 7a shows a 30 km vertical cross-section in the direction of the mean wind (NW to SE, Figure 7c). The city of Toulouse is situated in the centre between 10 and 20 km (black strip). The mean potential temperature averaged between 13.30 and 14.30 UTC, shows a cell distribution some kilometres downwind of the city to the NW with a horizontal extension of approximately 7-9 km. Warm air from the surface convects over the city until 1700 m (304.5 K). An anomaly elevation (100-150 m) of the ABL is advected leeward to the city.The large scale gradient of temperature pointed out with aircraft observations by Hidalgo *et al.* (2008), is visible in this vertical cross-section. The large scale gradient of temperature is oriented NW-SE were a difference of 300 m between the ABL height is presented. The daytime urban heat island of 1-1.5 °C is able to enhance up draft motions over and leeward the city centre with mean vertical velocities on the order of 1-1.5 m s^{-1} (not shown).

5.3 The urban-breeze circulation

Using aircraft data, Hidalgo *et al.* (2008) have studied the perturbation of the wind in the ABL created by the city. Surface convergence at 350 m and 1100 m towards the city was observed with an intensity of 1-2 m s^{-1} and an horizontal extension in the axis SE-NW 2 to 3 times bigger than the size of the city. The divergent return observed in upper levels at the top of the ABL (1650 m), reached 2 m s^{-1} at 13.00 UTC.

The dynamics of this local circulation is studied here comparing URB(M3) and RUR(M3). The perturbation created by the city in the mean wind field during the aircraft flight period (12.30-15.30 UTC) was calculated from the simulations outputs. A temporal average of the wind field for each grid point was done for URB and RUR and the difference of these two mean fields was computed. The result ($URB_{12h30\text{-}15h30}$ –

$RUR_{12h30\text{-}15h30}$) is shown as a vertical cross-section in the direction of the mean wind (NW-SE) in Figure 7a. The section of 30 km long, crosses Toulouse in city centre and ends near Merville city in order to cover the two sites (urban and rural) from where the radiosondes were launched during the IOP5 (Figure 7b).

The TEB scheme in the simulation URB allows to take into account the two processes cited in section 5.1: the surface energy balance and the roughness of Toulouse. This anomaly contains then the thermal and mechanical differences between both simulations. The roughness force effect, in terms of anomaly, emphasizes the branch of the breeze downstream of the wind field and over the city only in the first 100 m. Further above the convergent displacement of air towards the city centre at low levels that is observed from 150 m to 1100 m, is caused by the daytime UHI visible in Figure 5a and Figure 7. The intensity of this perturbation is of 0.5-1.5 m s^{-1} with a diameter of 20 km. The mixed layer at this hour is lower in the RUR simulation (1400-1500 m in RUR and 1500-1700 m in URB). The comparison between both simulations, results in a weak divergent return current from 1500 m to 1800 m off-centre to the NW of the city centre (Figure 8a).

5.4 Time-Evolution of the Breeze

In the radio sounding of 18.00 UTC, a north-westerly flow at the surface and a south-easterly flow at upper-levels was identified. This configuration indicated a convergent branch from the rural site (Merville, situated in the north-west) to the city and a divergent branch from the city centre to the rural site. The urban-breeze circulation of 5-6 m s^{-1} intensity, was able to dominate the flow pattern at this hour.

The same treatment than in section 5.3 was applied for the period 15.00 to 18.00 UTC in order to study the evolution of the breeze during the afternoon. The boundary layer grew from 1700 m at 13.00 UTC to 2200 m in the city centre and to 2100 m in the rural zone at 18.00 UTC. This well developed ABL allows the development of the breeze circulation both on horizontal and vertical directions. The anomaly with respect to the mean wind for the same cross section than in section 5.3 is shown in Figure 8b. The breeze circulation becomes stronger in the afternoon with an intensity of about 2-3 m s^{-1}. A convective cell off-centre to the NW of the city with a divergent return flow from 1800 m is visible during the afternoon. The cell situated leeward to the mean flux (NW of the city centre) creates a recirculation of the air with a diameter of 20 km and 1500 m of height.

6. Conclusions

This study is focused on the numerical simulation of the urban-breeze circulation observed by Hidalgo *et al.* (2008) over the city of Toulouse during the CAPITOUL experiment. High resolution numerical simulations were used to simulate and study the 3-D mesoscale urban effects difficult to observe.

Two numerical simulations were performed with the mesoscale atmospheric MesoNH model, a realistic situation (URB) and a second one (RUR) where the urbanized areas have been removed. Four nested models were used, with 12 km, 3 km, 1 km and 0.25 km resolution. The meteorological conditions simulated at the regional scale and the thermodynamical properties of the ABL were compared with experimental data from ground stations, wind profilers, radio soundings and aircraft data.

For the period of the breeze (12.00 to 18.00 UTC), the model is able to simulate the surface energy balance and the surface potential temperature for each zone (urban, residential, non-residential and rural zones). The heat island observed during this period with an intensity of 1 °C to 1.5 °C was caused by a difference of 200-300 W m^{-2} on sensible heat flux (Q_H) between the city centre and the rural zones. This heat island is an important element for the generation and persistence of the urban-breeze circulation observed this day.

MesoNH simulates the horizontal and the vertical extension of the UHI within the ABL. The location (advected some kilometers from the city centre to the NW) is also well represented. The anomaly of the ABL height leeward to the mean flow observed by Hidalgo *et al.* (2008) was verified and analysed here. This anomaly of the ABL height (300 m) leeward to the mean flow is due to enhanced up-draft motions over and leeward to the city centre. The horizontal extension of this temperature anomaly is approximately 7-9 km. The ABL stays more developed leeward of the city with an entrainment zone 150-200 m higher than over the city centre due to a large scale horizontal gradient of 1°C oriented NW-SE.

The dynamical perturbation on the ABL due to roughness, was analysed for the period 09.30-11.30 UTC when the UHI intensity is minimal. The deceleration of the large-scale wind due to the roughness of the city is of 1.5 m s^{-1} at the surface and decreases fast on the vertical to become negligible at a height of 100 m.

While the perturbation on potential temperature has a global size of the order of the whole city size, the perturbation on the wind field due to the buoyant convective processes is of the order of 2 to 3 times the size of Toulouse. The urban-breeze circulation started in the early afternoon with a convergent displacement of air towards the city centre at low levels of 0.5-1.5 m s^{-1} of intensity and a horizontal extension in the axis of the mean wind (SE-NW) of 20 km. A divergent return current from 1500 m to 1800 m off-centre to the NW of the city centre was present at upper levels. In late afternoon the growth of the ABL height from 1700 m at 13.00 UTC to 2200 m of height in the city centre at 18.00 UTC allowed the enhancement in intensity, horizontal and vertical extension of the urban-breeze circulation.

Appendix: Evaluation of the improvement on the ABL thermodynamics representation when going down to 250 m of horizontal resolution instead of 1 km.

For this study four two-way, grid-nested models are used with horizontal grid resolution of : 12 km (M1), 3 km (M2), 1 km (M3) and 0,25 km (M4) (Figure 1a, b and c). The resolution of 250 m in the last domain allows the explicit representation of the largest turbulent motions in the diurnal Urban Boundary Layer. A quasi-1D (on the vertical) scheme is sufficient to represent turbulence for the first three models. A mixing length computed using the Bougeault (1989) scheme is used. In last model horizontal gradients must be solved and a 3D scheme (Cuxart *et al.*, 2000) is used, able to see turbulence sources by shear in all three spatial dimensions.

The objective of this appendix is to estimate the benefit obtained in the thermodynamic fields representation of model URB(M3) (1 km resolution) when the model M4 (0.25 km resolution) is run in a 2-way-grid-nesting mode. In other words, is evaluated the improvement on the simulated urban effects (e.g. UHI) in the UBL when a higher resolution of 250 m is used instead of a resolution of 1km only. An extra run, URB(M3)-1km, was performed using only M1, M2 and M3 models (so domain M4 is not used and the finest resolution is 1 km).

The horizontal pattern of potential temperature at 350 m (Figure 9a and Figure 9b) and 1100 m

(Figure 9c and Figure 9d) of height are presented for simulations URB(M3) and URB(M3)-1km at 14.00 UTC. The UHI simulated by URB(M3) (so with the M4 at 0.25 km of resolution runs in a 2-way-grid-nesting mode, Figure 9a and Figure 9c) is a little advected off-centre to the north-west of the city with an horizontal extension in the transversal direction (SW-NE) comparable of that in the mean wind direction (SE-NW). However, the UHI simulated by URB(M3)-1km (so without a M4 nested model, Figure 9b and Figure 9d) is elongated in the large scale flow direction (SE-NW) spreading the urban heating to much to the north-west of the city concentrating it in a narrow band.

The model URB(M3)-1km can not explicitly solve turbulent motions with a resolution higher than 1 km. The turbulent scheme (1D) has problems to mix in the horizontal direction at this resolution and, in this case, the advection tends to lengthen the UHI in the wind direction flow. Even using a 3D turbulent scheme the result will be similar due to much weaker horizontal gradients.

In URB(M4) the dynamics are quasi-LES type: the largest turbulent motions are resolved explicitly by the advection of the model. Therefore the turbulent exchanges are more realistic, especially for the ones transverse to the mean wind flow, thanks to the thermals in the UBL. M3(URB) simply averages spatially these LES-like motions of M4. So it takes into account correctly the turbulent exchanges down to the scale of 250 m of resolution.

Is particularly critical here to have a good representation of fine scale turbulent motions because Toulouse city is not very wide. When a classical 1 km resolution alone is used, then the lateral exchanges are smaller due to the lack of turbulent fluxes, either resolved (there is no significant transverse turbulent motions resolved by advection) or parameterized. This explain for example why lagrangian models are often coupled to mesoscale ones for dispersion studies: the lack of lateral turbulence (through the thermals for example) in the mesoscale models is replaced by a statistical representation of the plumes (e.g. with gaussian models, see Lac. *et al.*, 2008).

However, when the process under study is not only on a passive component of the atmosphere (as a tracer) but as here on the small-scale thermodynamical fields themselves (UHI, urban-breeze), then an excellent representation of the turbulence in the mesoscale model is mandatory. Using LES-like resolutions with adapted 3D turbulence schemes is a way to solve this problem.

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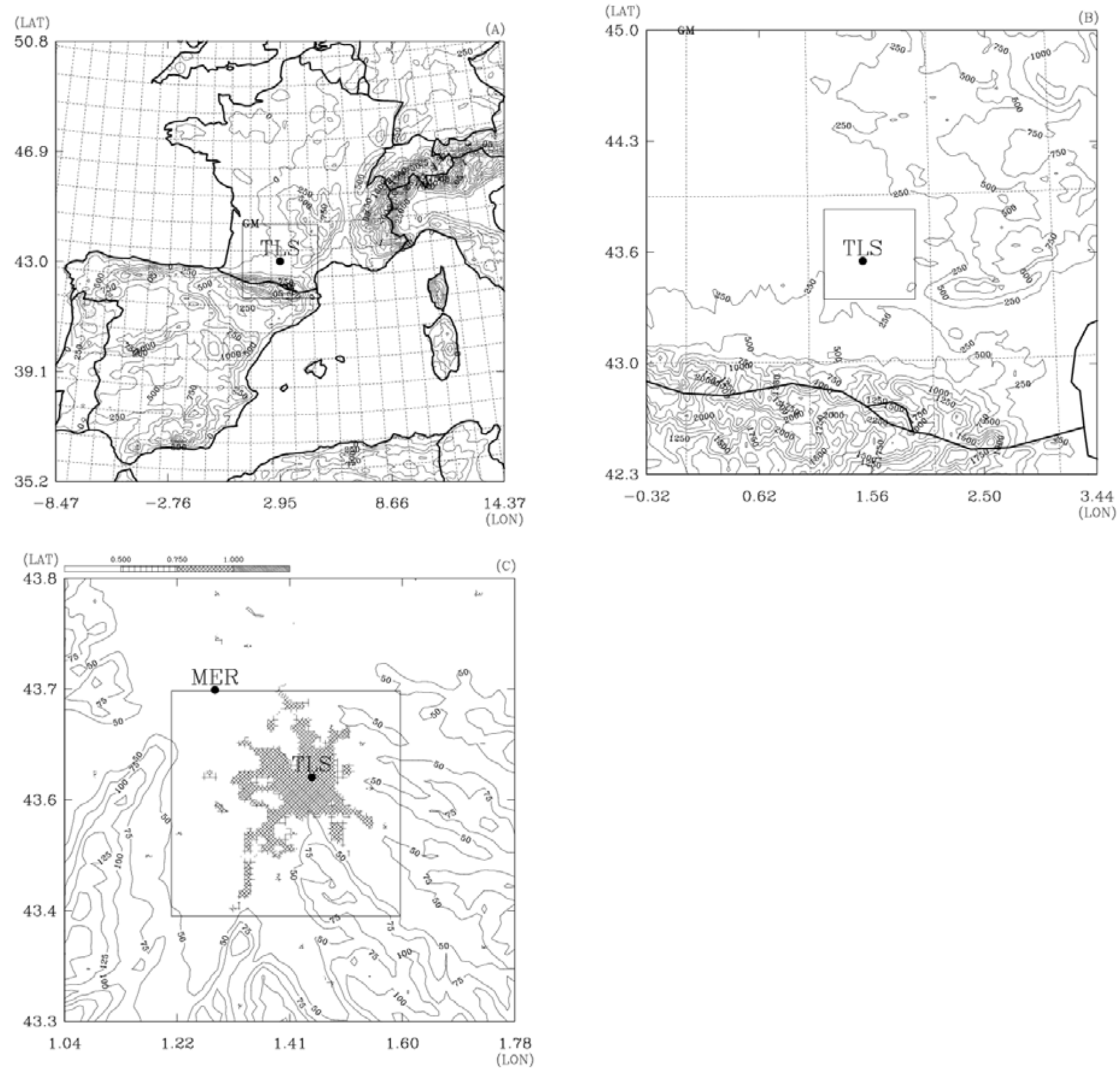

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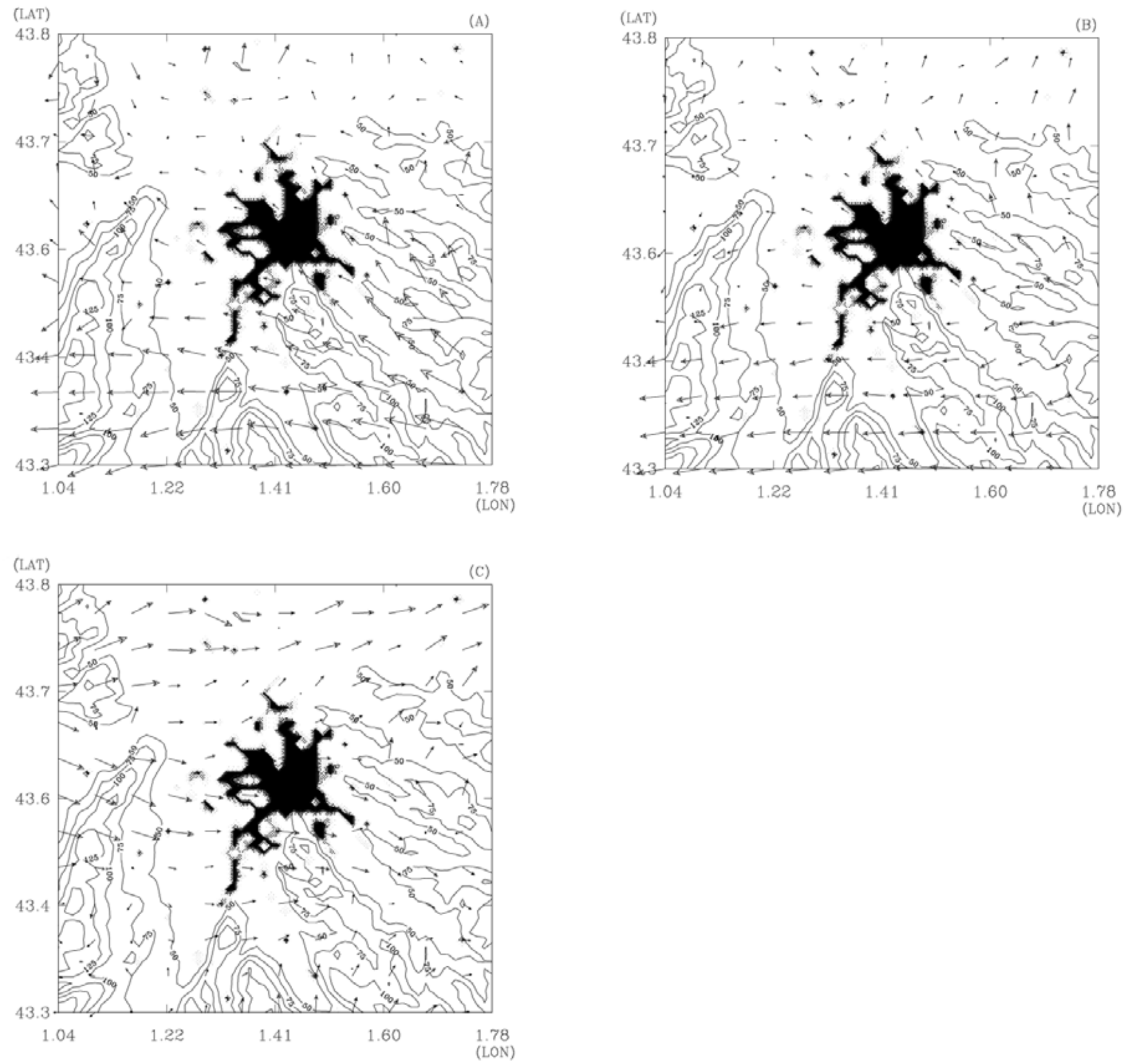

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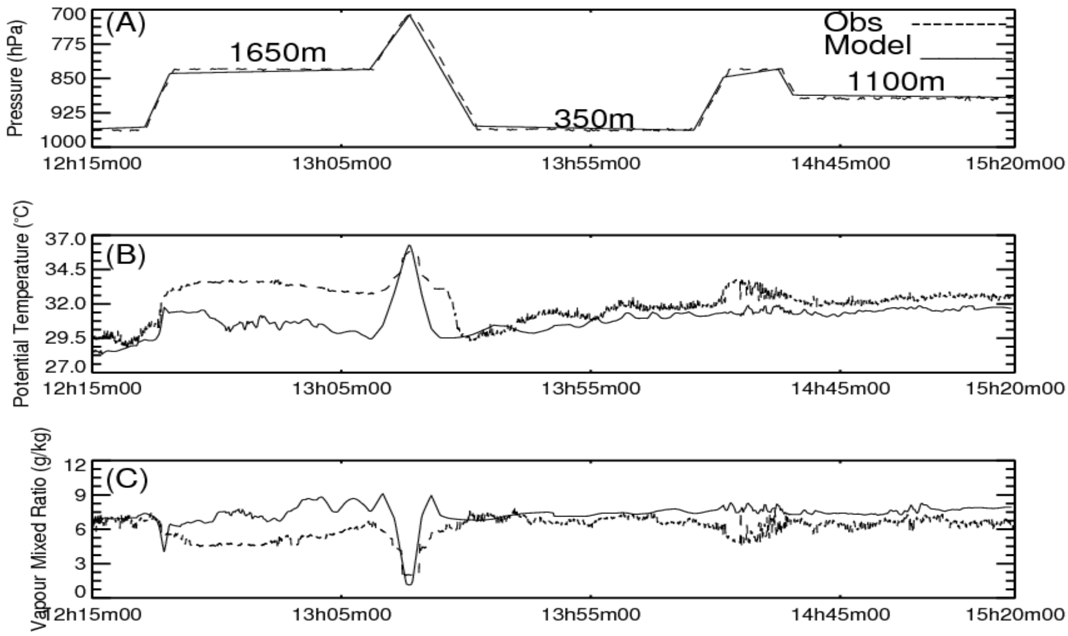

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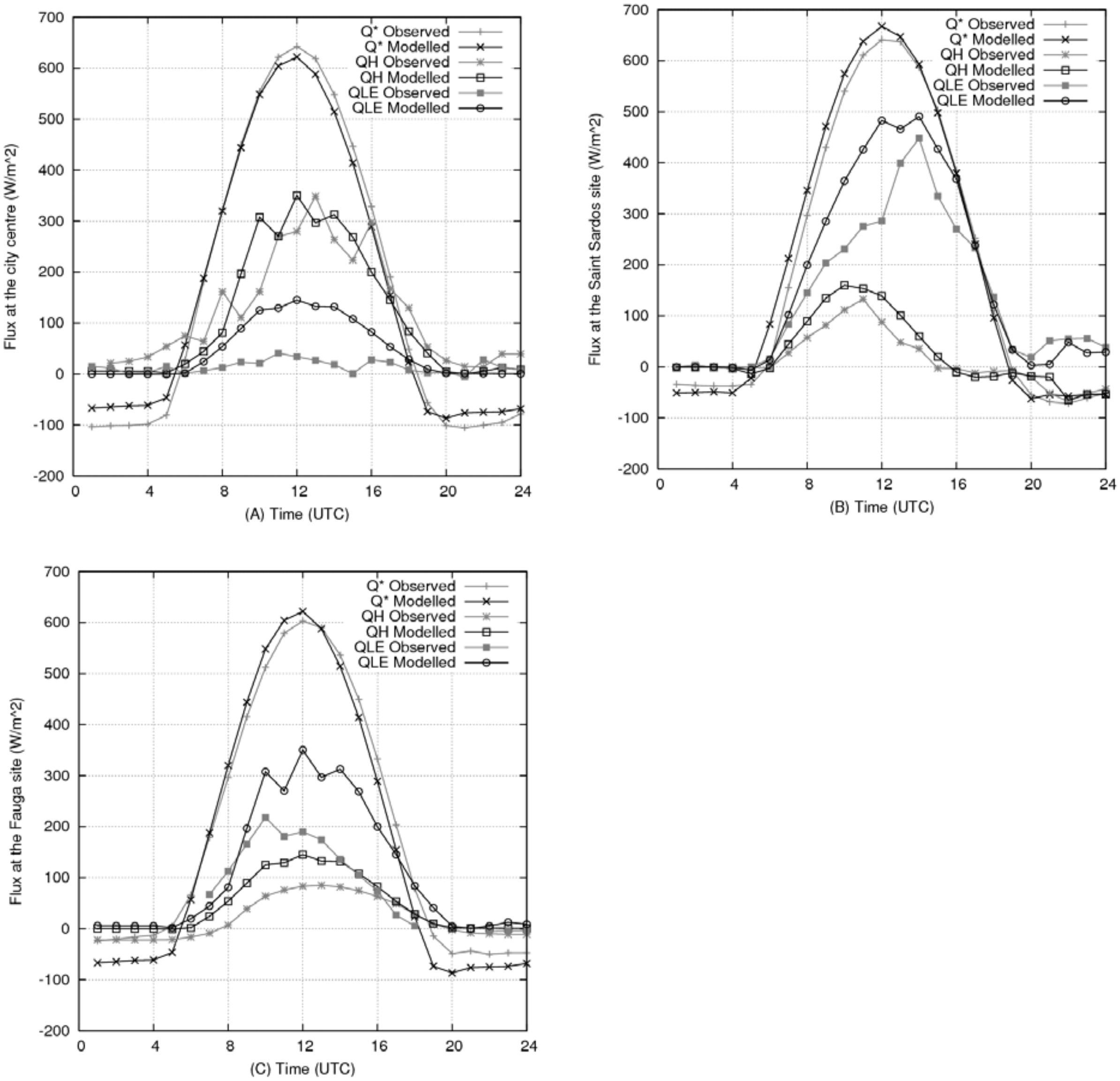

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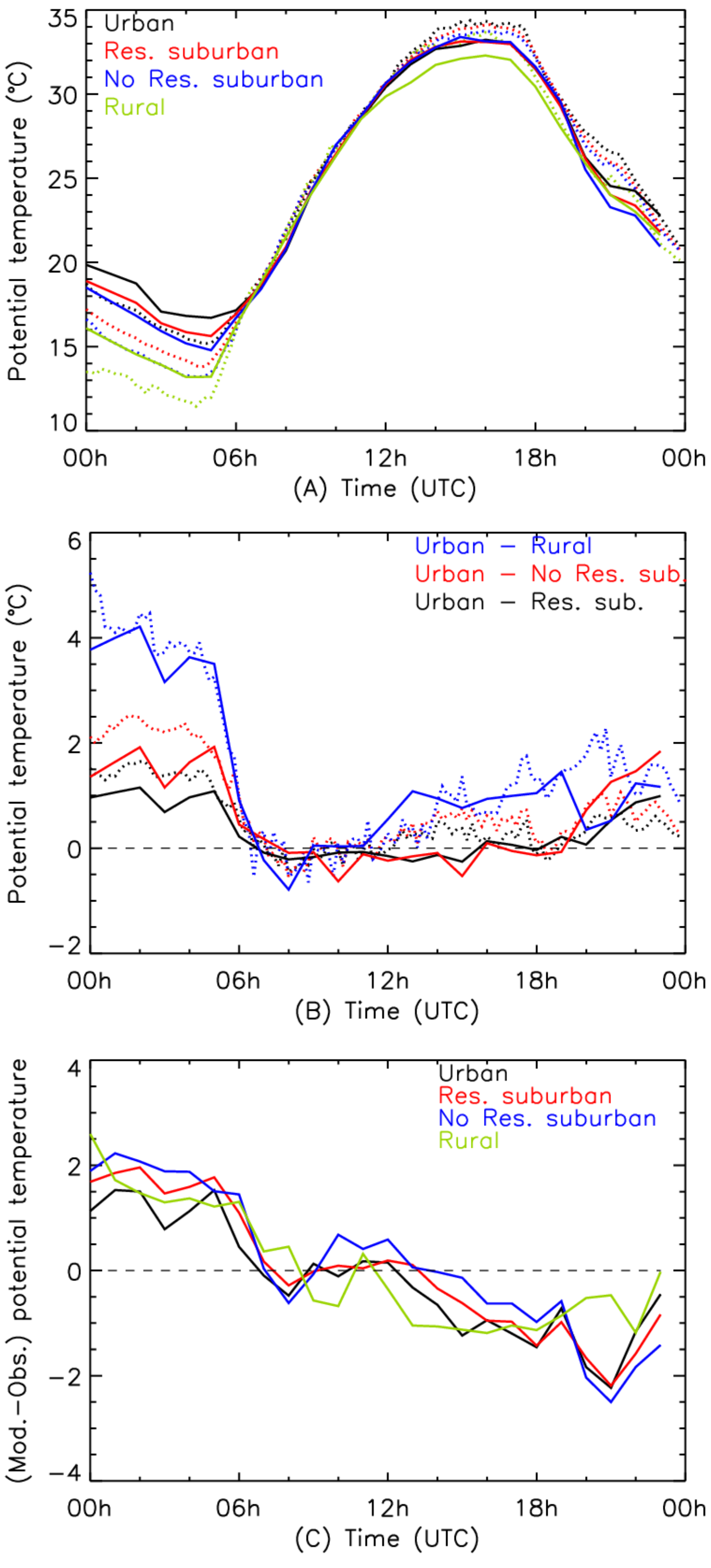

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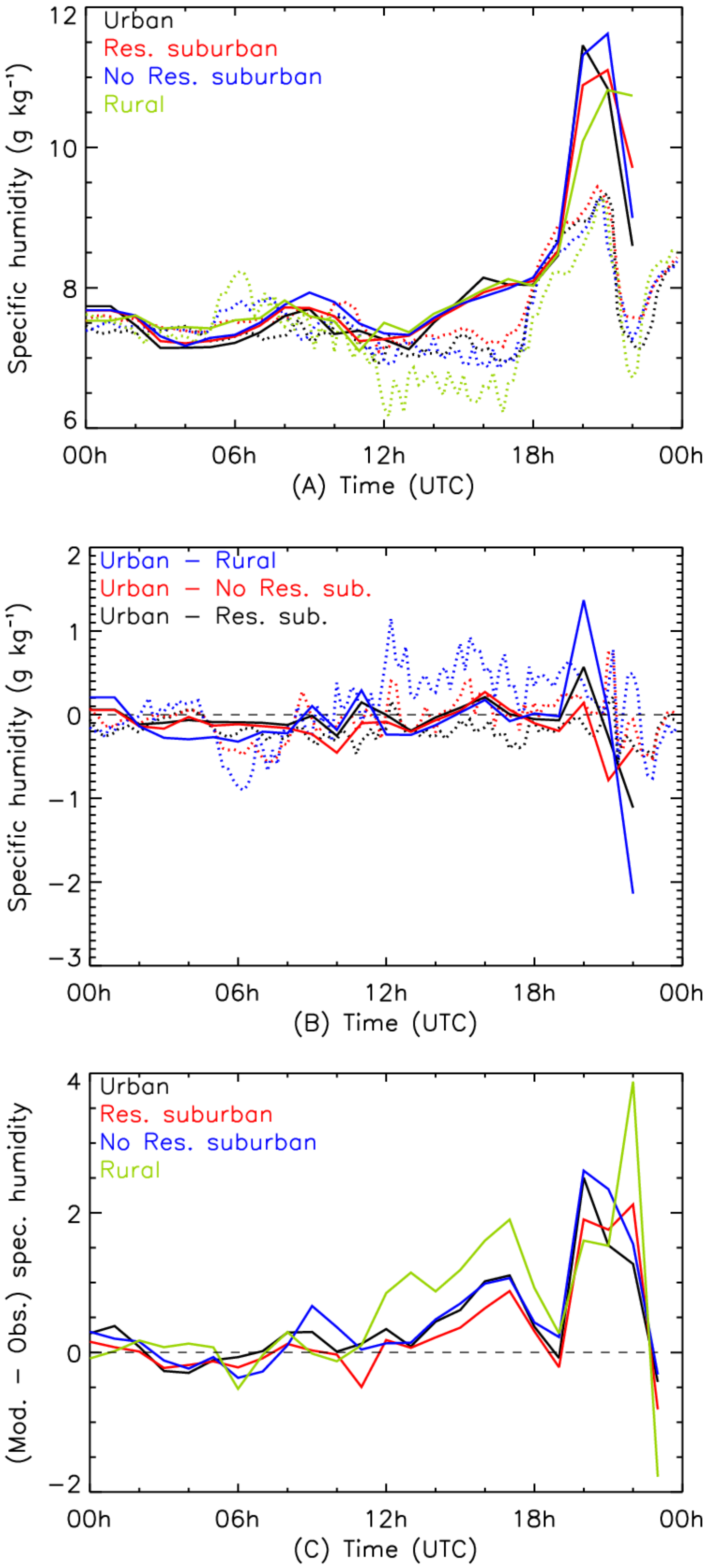

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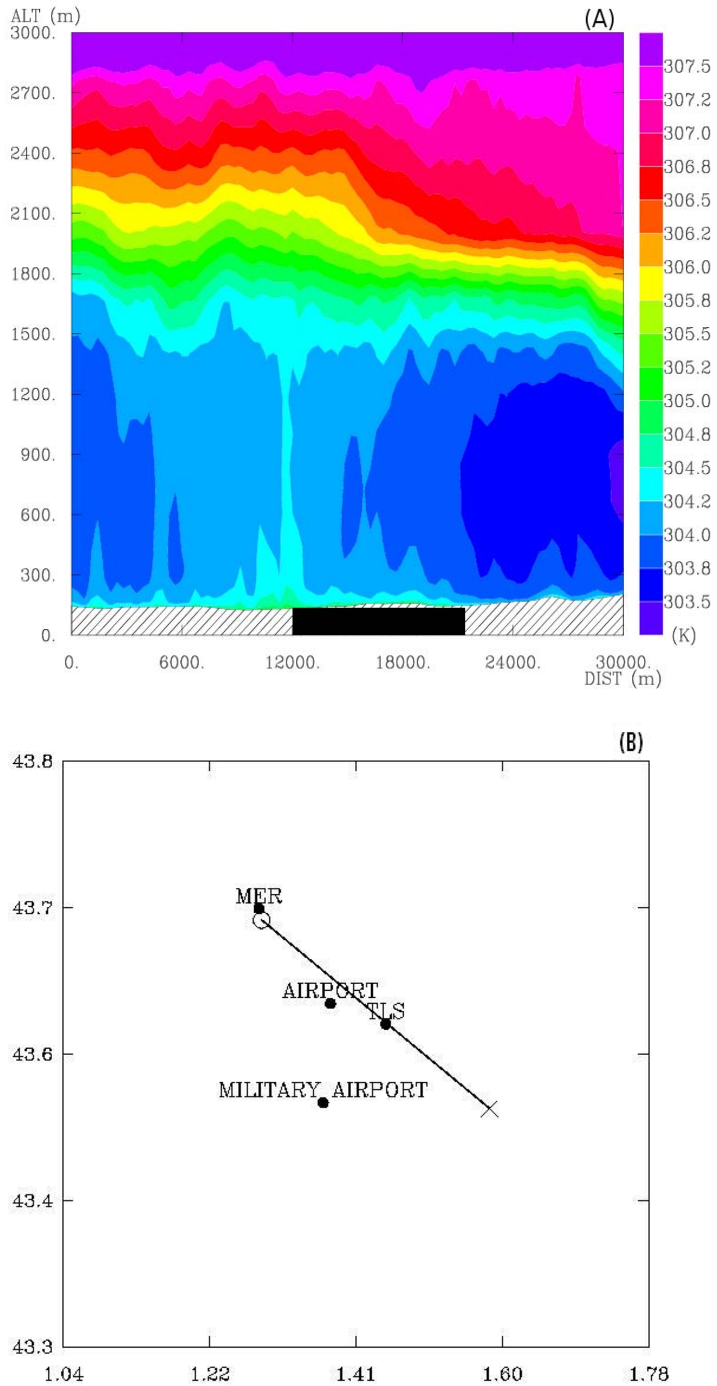

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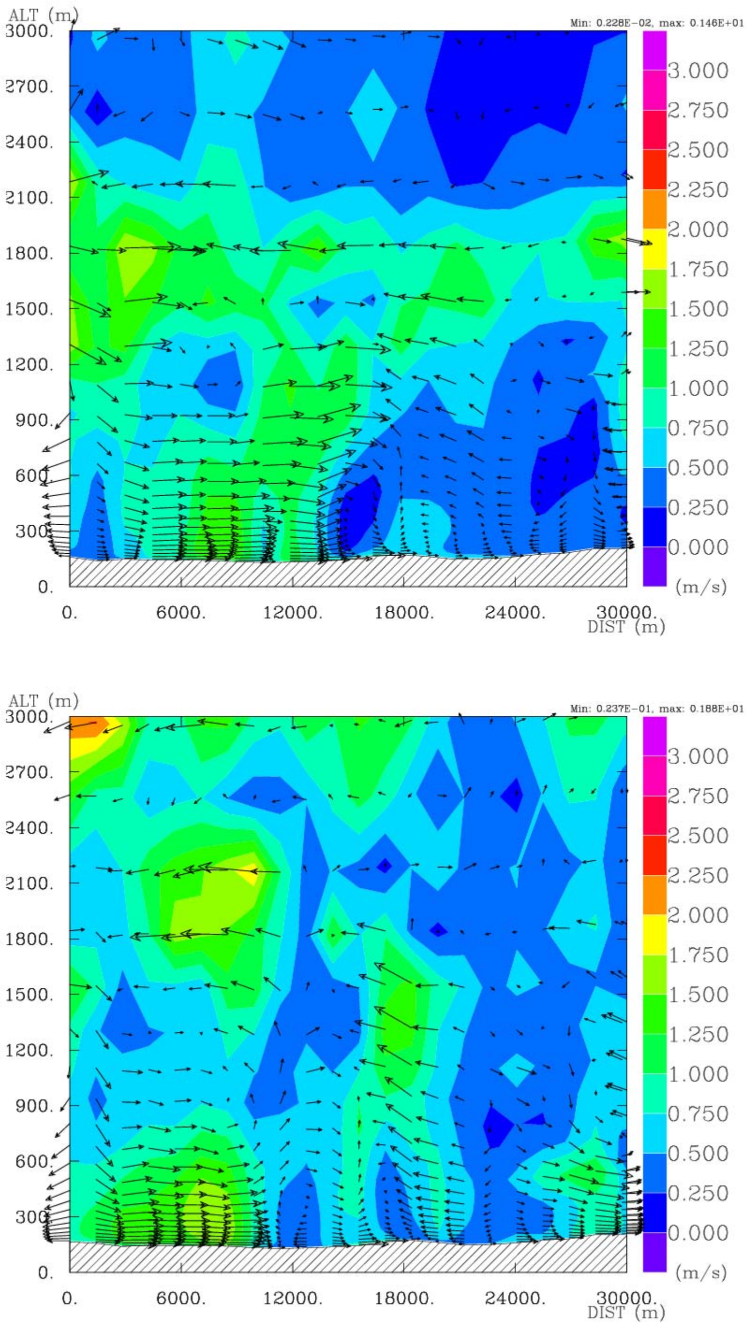

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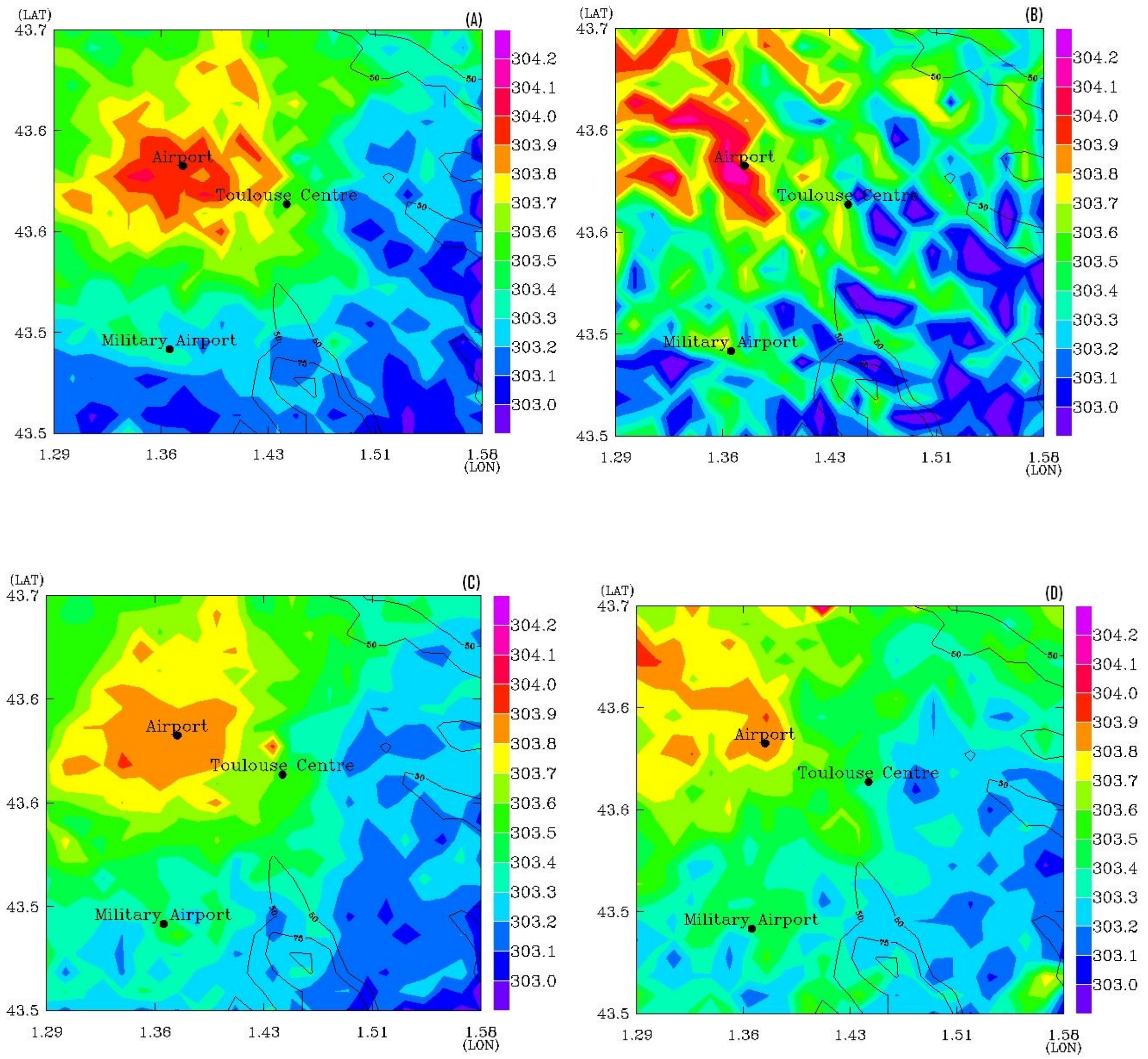

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Chapter 4

A Theoretical approach: Scaling the daytime Urban-Breeze Circulation

From a theoretical point of view, little has been done on the daytime urban-breeze circulation in a hinterland city contrary to its analogous in a coastal environment the *sea-breeze circulation*. Historically, the sea-breeze circulation for simplicity has been studied using a two-dimensional coordinate system and an infinite straight coastline (Walsh, 1974; Niino, 1987). Urban-rural circulation are similar to the problem of an island heated during daytime and it surrounding sea where a cylindrical coordinate system are used (Smith, 1957). The influence of the UHI on the large-scale atmospheric flow pattern can be studied in the context of the response of the flow to specified surface or finite-depth heating which represents temperature excess in the heat island region (Olfe and Lee, 1971). The theoretical studies of the horizontal temperature advection generally fall in three categories: analytical studies, studies based on experimental data and non-linear numerical modelling simulations.

Analytical studies are based on idealised solutions of the time-dependent conservation equations that employ various degrees of linearisation. The analytical resolution of these equations is complex, and for this reason, approximations are used to simplify the governing equations. Analytical studies directed toward the UHI were developed in the 1970s and 1980s (Olfe and Lee, 1971; Lin and Smith, 1985, Lin 1987). Analytical studies combined with experimental data from laboratory studies using a water tank were performed by Lu *et al.* (1997a), Lu *et al.* (1997b) and Cenedese (2003). Currently, there are insufficient observational data sets of urban-breeze circulation to obtain the scaling laws as done by Steyn (1998) and Steyn (2002) for sea- breeze circulation. When computational numerical models were available, analytical studies combined with two-dimensional numerical calculations were used by Richardone and Brusasca

(1989), Baik (1992, 2001), Yoshikado (1992) and Baik and Chu (1997).

Most of the studies cited here are concerned with essentially night-time conditions under stable atmospheric conditions. Day- and night-time differences in urban-breeze circulation were studied by Yoshikado (1992) and Cenedesse (2003), who both used the Lu *et al.* bulk convection model for daytime conditions. Both studies focused on the UHI interaction with the daytime sea breeze. To date, no study has focused in depth on daytime urban-breeze circulation and a comprehensive, fundamental investigation is still necessary.

In previous studies, the heat flux at the surface and the turbulent thermal diffusion processes were not directly coupled; instead, the thermal forcing was prescribed directly (Olfe and Lee, 1971; Lin and Smith, 1986; Baik and Chun, 2001). As indicated in numerous works by Baik (1992), Baik and Chun (1997) and Baik and Chun (2001), numerical models with detailed physics would be more appropriate than models with a specified heating distribution. Mesoscale numerical models that have advanced parametrisations can be used to reproduce mesoscale circulations. Idealised numerical simulations reduce the dependence of scaling laws on site-specific features, such as topographic influences, climatological urban-rural temperature gradient, surface layer heat flux regimes, and surface roughness.

Scaling is a well-known approach for describing circulation and turbulence in the Atmospheric Boundary Layer (Stull, 1997). Its basic assumption is that the structure of the ABL can be described in terms of only a few characteristic governing parameters. An example is the Monin-Obukhov similarity theory for the surface layer (Obukhov, 1946; Monin and Obukhov, 1954). They define the surface-layer length scale (**L**) as a measure of the vertical extent of mechanical and wind shear effects on turbulence production. The application of the Monin-Obukhov theory has been limited to the lowest 10-100 m above the ground. An equally simple and general method to describe the flow above the surface layer can not be developed because external forcing parameters become too complex, especially due to the instationnarity of the flow (and the dependency on the height of the ABL since sunrise). However, for some specific phenomena, scaling can be appropriate, as for the sea-breeze scaling by Steyn (2002).

Nondimensional parameters for a problem can be determined in two ways. They can be deduced directly from the governing differential equations if these equations are known. When the governing differential equations are unknown, then the nondimensional parameters can be detemined by performing a simple dimensional analysis on the variables involved.

3D high resolution numerical simulations is the strategy chosen here to examine the physical processes dependence on the external forcing involved in the daytime urban-breeze circulation. A set of simulations performed with the non-hydrostatic Meso-NH atmospheric model, provides a set of urban-breeze circulations forced by an idealized urban environment. The objective is to develop a set of simple scaling laws describing the urban-breeze features in function of a selected governing variables.

Scaling the Daytime Urban-Breeze Circulation

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Abstract: The urban-breeze circulation is a mesoscale response of the atmospheric flow that is related to horizontal variations in temperature associated, for dry conditions, with gradients in sensible flux densities. An original scaling of the daytime urban heat island and urban breeze characteristics has been developed. Three-dimensional high-resolution numerical simulations, performed with the non-hydrostatic atmospheric model Meso-NH, were used to generate a set of urban-breeze circulations forced by an idealised urban environment. The pertinent forcing parameters chosen are the size of the city, the height of the thermal inversion that tops the mixed turbulent air layer and the difference (urban-rural) of surface heat flux. Scaling laws, describing the urban heat island form, the horizontal and vertical wind intensity and profiles are presented.

Keywords: Urban-breeze, scaling, heat island, Meso_NH,

1 Introduction

The urban-breeze circulation is a mesoscale response of the atmospheric flow that is related to horizontal variations in temperature that is associated, for dry conditions, with gradients in sensible flux densities. The UHI is then the source of the urban-breeze circulation, and the horizontal structure is characterised by the urban surface being warmer than its surroundings. Due to the thermally induced horizontal pressure gradient, convergent motions towards the city core are formed at lower levels, with divergent motions being formed above. As a result, the warmer air rises over the city and a local circulation begins, with colder air from the countryside being drawn in over the city centre (Figure 1a). The daytime urban-breeze was documented by Wong and Dirks (1978) and Hidalgo *et al.* (2008a) using aircraft data from the field campaigns of METROMEX (St. Louis, 1974, Changnon, 1981) and CAPITOUL (Toulouse, 2004-2005, Masson *et al.,* 2008) respectively. Urban-breeze circulation has also been studied numerically using an atmospheric numerical model coupled to an urban SEB model. For example, simulations were carried out by Lemonsu and Masson (2002) over Paris (France) and by Hidalgo *et al*. (2008b) over Toulouse (France) using the mesoscale atmospheric model Meso-NH (Lafore *et al*., 1998) coupled with a TEB urban scheme (Masson, 2000). The latter study has demonstrated the role of the surface energy balance in the development of low-level airflow convergence towards city centres.

Theoretical studies, focusing on urban-breeze scaling, generally fall into three categories: analytical, observational, and non-linear numerical modelling. Analytical studies are based on idealised solutions of the time-dependent conservation equations that employ various degrees of linearisation. The analytical solution is complex, so approximations are used to simplify the governing equations. Analytical studies directed toward the UHI were developed in the 1970s and 1980s (Olfe and Lee, 1971; Lin and Smith, 1986; Lin 1987) Experimental data from laboratory studies using a water tank are described in Lu *et al.* (1997a), Lu *et al.* (1997b) and Cenedese (2003). Currently, there are insufficient observational data sets of urban-breeze circulation to obtain the scaling laws as done by Steyn (1998) for sea-breeze circulation. Two-dimensional numerical calculations were used by Richardone and Brusasca (1989), Baik (1992) and Yoshikado (1992) and more recently by Baik and Chu (1997) or Baik (2001).

Most of the studies cited here are centred essentially on night-time conditions under stable atmospheric conditions. Only two authors have studied day- and night-time differences in urban-breeze circulation, Yoshikado (1992) and Cenedese (2003), who both used the Lu *et al.* bulk convection model Lu *et al.* (1997b) for daytime conditions. Both studies focused on the UHI interaction with the daytime sea-breeze. To date, no study has focused in depth on daytime urban-breeze circulation in a hinterland city.

In previous studies, the heat flux at the surface and the turbulent thermal diffusion processes were not directly coupled; instead, the thermal forcing was prescribed directly (Olfe and Lee, 1971; Lin and Smith, 1986; Baik and Chun, 2001) . As indicated in numerous works by Baik (Baik, 1992; Baik and Chun, 1997; Baik and Chun, 2001), numerical models with detailed physics are more appropriate than models with a specified heating distribution. This approach was used by Kurbatsky (2001) using a model with a prescribed heat flux at the surface to verify the scaling of Lu *et al.* (1997) for the nocturnal UHI.

Porson (2007) showed that mesoscale models that have advanced parametrisations can be used to reproduce mesoscale circulations. Idealised numerical simulations reduce the dependence of scaling laws on site-specific features, such as topographic influences, climatological urban-rural temperature gradients, surface layer heat flux regimes, and surface roughness. In the literature, no study uses 3-D numerical simulations to examine the physical processes involved in daytime urban-breeze circulation. The aim of this paper is to investigate how external forcing controls the speed and the vertical and horizontal length scales. In this study, 3-D high-resolution numerical simulations, performed with the non-hydrostatic atmospheric model Meso-NH, were used to generate a set of urban-breeze circulations forced by an idealised urban environment.

2. Physics of the problem

The scaling technique is a well-known approach used to describe turbulent flow. Its basic assumption is that, for some specific meteorological conditions, the structure of the lowest kilometers of the atmosphere (directly influenced by the earth surface) can be described in terms of only a few characteristic governing parameters (Holstang and Nieuwstadt, 1986) Scaling laws for nocturnal UHI have been developed by Lu *et al.*(1997a, 1997b). The aim of this section is to provide a set of scaling laws for the UHI and urban breeze circulation under daytime conditions.

2.1 Current theory relating to the noctural UHI and the urban-breeze

During the night, a stable layer of air generally forms in rural areas, due to surface cooling. Under calm wind conditions (i.e. conditions favourable to the formation of the UHI), there is no mixing of the air by wind shear and the nocturnal stable layer inversion is strong. This inversion is typically characterised by its potential ambient temperature gradient ($\partial\Theta_a/\partial z$, Figure 2), or alternatively, by the Brünt-Vaissala frequency N = $(g/\theta\ \partial\Theta_a/\partial z)^{(1/2)}$. This nocturnal inversion can reach a few hundred metres in height. Over a city, however, the SEB is modified and the air is heated by the surface. This reduces the cooling of the atmosphere but is not strong enough to prevent it. However, it is sufficient to maintain mixing with the air above by dry convection. This leads to the development of a neutral or slightly unstable turbulent layer above the city (Figure 2). Therefore, during the night, this ambient stability plays a key role in determining both the UHI intensity and the strength of circulation (Scheffler, 1978, 1979; Vukovich and Dunn, 1978; Richardone, 1989).

Lu *et al.* (1997a) studied the UHI circulation in such a stratified environment by adimensionalising the governing equations of motion in an axisymmetric cylindrical coordinate system. A stratified atmosphere was assumed. The Coriolis force, internal heat generation, and radiation were ignored. Furthermore, the surface heat flux in the countryside was considered negligible (but its consequence over time, which leads to the strongly stratified nocturnal inversion, was considered).

Lu *et al.* (1997a) showed that, under the stated (typically nocturnal) conditions, the UHI can be properly modelled by combining only three external (or forcing) parameters:

- the characteristic diameter of the city: D (m)
- the ambient thermal stratification, characterised by its Brunt-Väissälä frequency: N (s^{-1})
- the surface heat flux of the city : H_u (m K s^{-1})

Note that the surface heat flux can be retrieved directly from the corresponding surface heat flux in the SEB by: Q_H (W m^{-2}) = $\rho C_p H_u$ (where ρ is the air density, typically 1.2 kg m^{-3} at low altitudes; C_p = 1004 J K^{-1} kg^{-1} i.e. the heat capacity of air at constant pressure).

Using a scale model (water tank) and an analysis of the equations, the authors defined several scales, namely:

- D as the length scale
- $U_D = (\beta D H_u)^{1/3}$ as the radial (horizontal) velocity scale; where $\beta = g\Theta^{-1}$
- $W_D = U_D F_r$ as the vertical velocity scale. $F_r = U_D/ND$ (the Froude Number)
- $U_D N/(g/\theta)$ as the temperature scale.

Combining these scales allows scaling laws to be obtained for unknown properties of the flow, as defined for the authors' tank experiment.

The scaling law obtained for the UHI intensity as a function of governing variables is

$$UHI = 1.61 U_D N/(g/\theta)$$

The nondimensional structures of the UHI and of the flow velocities were also obtained by Lu *et al.* (1997a, 1997b).

2.2 Daytime UHI and urban-breeze: environment description

During the day, the structure of the lower atmosphere is completely different from its structure at night. In the countryside, the heating of the surface by the sun in the morning produces a heat flux towards the air above that is sufficient, firstly, to destroy the nocturnal stable layer and, secondly, to mix the air (the so-called 'mixed layer', in Figure 2) by turbulence to a much higher altitude (z_i), where a capping temperature inversion occurs. This temperature inversion is linked, not to the nocturnal stable layer (which is near the surface), but more to the previous day's capping inversion (which is still present above the nocturnal inversion, shown by dashed lines on Figure 2), to the general meteorological situation and the total heating of the air by the surface during the day. This inversion altitude, z_i, varies typically between 500 m (in winter) to 2000 m (during some hot days in summer).

The presence of a city will modify the SEB by heating the atmosphere above it. However, this modification only represents a relatively minor modification of the countryside mixed layer: the UBL will be a little warmer (the daytime UHI), a little more turbulent, and extend slightly higher.

The urban-breeze will therefore influence the atmosphere up to the capping temperature inversion at altitude z_i. Apart from this, there is no major effect on the stability. The countryside mixed layer in which the urban breeze develops is unstable. The capping thermal inversion is very stable (most often more than any nocturnal stable layer), so its exact stability value in itself is not significant. The fact that it acts as a lid, blocking upwards motions of air from the surface, is the more important point. The Brunt-Väissälä frequency is then no longer a useful parameter in describing the environment of the UHI and the urban breeze, being replaced by the inversion height parameter z_i.

A further difference from the nocturnal case is that during the day, the surface heat flux in the countryside can be significant. In the morning, at least, the surface heat flux is sufficient to build up the mixed layer, and more often than not, it remains positive during the entire day. However, the countryside heat flux is lower than the urban equivalent, because the plants consume a large part of the available solar energy for latent heat. This difference in the heat flux between the city and the countryside is what causes the UHI and the urban-breeze circulation to occur during the day. As a consequence, this parameter is highly relevant for this study. Hereafter it noted by (H_u - H_r).

2.3 Daytime UHI and urban-breeze: scaling laws

Once the forcing parameters of the problem have been identified, the general form of the scaling laws of each quantity of interest (i.e. the UHI or breeze intensity), can be deduced using similarity theory. This is based on the use of a non-dimensional number obtained using the parameters of interest to the study, and the Pi theorem of Vaschy-Buckingham (Buckingham, 1914).

The Pi theorem requires that all the governing parameters (forcing, internal forces, and independent variables) that influence the UHI or the urban breeze be identified. The pertinent forcing parameters are:

- the diameter of the city: D (m),
- the ambient capping inversion height: z_i (m)
- the difference of surface heat flux between the city and the countryside: (H_u - H_r) (K m s^{-1}).

The present study is limited to the case with no mean wind (it would be a forcing parameter in more general case), so this parameter is not taken into account.

The main internal force that influences these physical phenomena is gravity. The heated air at the surface has a lower density than the surrounding air, and so will move upwards relative to the colder (so denser) air above it. This feature could be represented by the gravitational constant g, but it is more common to use the buoyancy coefficient $\beta = g\Theta^{-1}$ in atmospheric problems (where the Boussinesq hypotheses are valid). For the urban breeze, given that short periods of time (an afternoon) will be considered, the Coriolis force (that would be characterised by its frequency *f*) will not be taken into account. Therefore, the unique internal force parameter is the buoyancy, β (m s^{-2} K^{-1}).

Independent parameters (that will be used when characterizing the non-dimensional shape of some characteristics of the urban breeze) are:

- distance to the centre of the city: x (m)
- altitude: z (m).

From these six external parameters, scales can be determined for distance (D_s), speed (W_s), and temperature (Θ_s), and these can be used to describe the intensity of the associated urban breeze characteristics. One non-dimensional number (z_i/D) will describe the relative influence of the city size to the capping inversion height. Two additional non-dimensional numbers (x/D and z/z_i) will be used only if a spatial description of the phenomenon is required. The three characteristic scales for distance, velocity, and temperature are:

- $D_s = D$
- $W_s = (\beta\ z_i\ (H_u - H_r))^{1/3}$
- $\Theta_s = (H_u - H_r)/W_s = (H_u - H_r)^{2/3}(\beta z_i)^{-1/3}$

The general form of the UHI and urban breeze can then be determined. The UHI intensity is: UHI = $\Theta s f_{UHI}(z_i/D)$. The horizontal shape of the UHI is given by: UHI(x/D) = $\Theta_s\ f_{UHI}(z_i/D,\ x/D)$. The vertical and horizontal intensities of the urban breeze are: $W_{breeze} = W_s\ f_w(z_i/D)$; $U_{breeze} = W_s\ f_u(z_i/D)$, and so on.

The problem is that none of the functions $f_\cdot$ in these general relations are known, and they cannot be determined from the similarity theory alone. Analytical simplifications, experiments, or numerical simulations must instead be used to estimate the final forms of these relationships. In the present paper, a numerical approach is taken.

3. Description and validation of numerical experiments

A set of 40 numerical simulations were performed using the Méso-NH atmospheric model to simulate the dynamics of the atmosphere (Figure 3). As shown in section 2.3, the difference between urban and rural surface turbulent sensible heat flux ($H_u - H_r$), the capping inversion (z_i), and the diameter of the city (D) were considered as the external forcing parameters (Figure 3). A set of these three parameters was chosen and fixed for each of the 40 simulations. Overall, z_i varied from 1000 m and 2500 m (with values taken every 500 m), D was equal to 10 or 20 km, and the SEB surface heat flux varied from 100 to 300 W m^{-2} with steps every 50 W m^{-2} (i.e. $H_u - H_r$ from 0.083 to 0.248 K m s^{-1} every 0.041 K m s^{-1}).

The simulation was performed with a horizontal grid resolution of 500 m, which is sufficient to study the fluid motions and properties at the urban scale. The effects of the perturbations created by the city in the mean flow had a horizontal extent two to three times the size of the city (Hidalgo *et al.,* 2008b). The horizontal domain (150 km x 150 km) was large enough to prevent interferences from the (cyclic) boundaries. The vertical coordinate was composed of 35 levels (5 km). The first atmospheric level was located 12 m above ground level. Eighteen levels were located in the first 1000 m. No water vapour was considered, the focus being done on the purely thermally induced circulation. The subgrid turbulence was parameterised following the schemes of Cuxart *et al.* (2000) and Bougeault and Lacarèrre (1989).

The meteorological context of the experiments were assumed using an idealised anticyclonic summer situation. The initial environmental temperatures were obtained from averaged data of the very sunny and calm days of the CAPITOUL experiment during the summer period (the selected days are the 4th, 15th, 28th and 31st July and 11th, 14th August 2004). The atmosphere was characterised by an idealised vertical profile representing a sunny summer day. The mixed layer (Brunt-Väissälä frequency N = 0 s^{-1}) had a vertical extension (z_i). At the top of the mixed layer, the capping temperature inversion layer of 50 m height with a strong stability (N = 0.06 s^{-1}) was located, allowing the control of z_i for each experience regardless of the surface heat flux imposed. Finally, the atmosphere above was represented by a stability of N = 0.01 s^{-1}. A period of three hours was simulated for each of the 40 simulations. Results are displayed for the 3rd hour of the simulation, by which time a quasi-steady state was reached with a well-developed urban-breeze circulation.

The ability of the model to reproduce accurately the urban-breeze in such idealised context is verified by comparing the results obtained with the D, z_i and (H_u - H_r) parameters of the urban-breeze event observed in Toulouse on the 4thJuly 2004 (Hidalgo *et al.*, 2008a) Consisting in a medium-sized city (D = 10 km) placed in the centre of the model domain, surrounded by flat land, with a initial well-developed mixed layer of z_i = 2000 m. The surface heat fluxes for urban and rural sites (Figure 4)(averaged for the six days mentioned above) are similar to those of the 4th July 2004 case. In the morning, the heat flux is also significant in the countryside (it reached 0.09 K m s^{-1} at 11.30 UTC), but during the period of interest in the afternoon, it is much weaker (it decreased to zero at 17.00 UTC). We assumed zero heat flux for the countryside in the period of interest. The time-averaged difference of sensible heat flux between the city centre and the rural site is of the order of 200 W m^{-2}. A value of (H_u - H_r) = 0.165 K m s^{-1} (200 W m^{-2}) was chosen.

Using these values for the forcing parameters, the model produced a near-surface UHI (first atmospheric level at 12 m of height) of 1.5 K, a horizontal wind speed in the convergent branch of the urban breeze reaching a maximum of 2 m s^{-1}, which compares well with the observations for a real city (Hidalgo *et al.*, 2008a). The 2 m s^{-1} vertical wind speed in the upward motion of the urban breeze over the city is slightly larger than that obtained for the more realistic simulation of the 4thJuly case (1.5 m s^{-1} (Hidalgo *et al.*, 2008b)). The simplifications made here in representing the physics of the UHI and urban breeze seem valid, allowing to vary the forcing parameters to define the scaling laws.

4. Scaling the daytime urban-breeze circulation

4.1 Simulated UHI and urban breeze features

Figure 5a shows the profiles of the mean near-surface temperature distribution as a function of the nondimensional distance (x/D) for the set of 40 simulations. The UHI intensity for different meteorological conditions (so different mixed layer heights z_i) varies for different values of (H_u - H_r). As the mixed layer height decreases, the available volume of air above the city for heating also decreases, and then the intensity of the UHI increases. For z_i = 2500 m, the UHI at the city centre ranges between 0.8 and 1.6 K, while for z_i = 1000m, it ranges between 1 K and 2.5 K. As expected, for a given mixed layer height, the stronger the surface heat flux over the city, the higher the UHI. Multiplying the heat flux difference by three increases the UHI intensity by a factor of two.

For given z_i and urban-rural heat flux difference, doubling the size of the city does not have a significant impact on the surface UHI. This has already been pointed out by Atkinson (2002) who concluded that the size of urban areas has a minimal effect on UHI intensity. Under daytime conditions, the reduced evaporation over cities (and hence the larger heat flux, associated with the higher (H_u - H_r)) is the most important factor. This is confirmed by the scaling laws below.

In the Lu *et al.* (1997a) experiments, the negatively buoyant region occupies 50% of the upper part of the (nocturnal) stable layer. The vertical temperature distribution (not shown) for our daytime simulations shows that 80% of the ABL endures strong positive buoyancy. A negatively buoyant region is situated in the upper part of the mixed layer.

Figure 5b and Figure 5c show the mean vertical profiles of radial velocity (averaged from x/D = 0.2 - 0.4) and vertical velocity (over the city centre, averaged from x/D = 0 - 0.2) as a function of the nondimensional height (z/z_i). The horizontal (convergent) velocity is at a maximum near the surface, at $0.05z_i$. The flow reversal height occurs around $0.6z_i$ - $0.7z_i$. Contrary to the UHI intensity, the vertical wind speed intensity is very sensitive to the diameter of the city, even if the absolute horizontal wind speed does not increase by much. This is due to the larger convergent area (the larger city), and also to the fact that a larger quantity of air is moving towards the city centre. Mass conservation then induces a larger vertical motion above the city centre. On the other hand, the increase of the vertical branch in the centre of the urban breeze as a function of z_i is simply caused by the additional buoyancy available. The higher the mixed layer, the higher the unstable layer inside it, and the longer the air parcels can accelerate vertically. A larger (H_u - H_r) also increases the buoyancy effect on W and slightly increases the horizontal wind convergence (at lower levels) and divergence (at higher levels).

4.2 A new set of scaling laws

The shape and intensity of the urban temperature anomaly, as well as the wind profiles, vary for each experiment as a function of the external fixed parameters. The scales defined in section 2.3 for length, wind, and temperature, combined with the nondimensional distance (x/D) and height (z/z_i), are used here to normalise these profiles, thus obtaining the laws that describe the features of the UHI and the urban-breeze circulation as a function of just three governing parameters (H_u - H_r, z_i and D).

4.2.1 Scaling the daytime UHI.

Figure 6a shows the normalised profiles of the UHI (UHI/(*Cte* Θ_s) = 1; with a normalisation constant *Cte* = 17.25) at the first atmospheric level (12 m) for the 40 simulations. The experiments simulate the top-hat type (peak, plateau, and cliff) spatial distribution of the UHI described by Oke (1987). A least square polynomial fit is used to obtain the optimal polynomial regression describing the UHI through the city. The relationship obtained is a cubic polynomial with the following coefficients:

$$UHI/17.25\Theta_s = 1.37(x/D)^3 - 1.78(x/D)^2 - 0.58(x/D) + 1$$

This equation gives the UHI intensity above the canopy, at different distances from the centre of the city as a function of only three (measurable) governing parameters, the size of the city (D), the boundary layer height (z_i), and the horizontal gradient of sensible heat flux between the city and its surroundings.

4.2.2 Scaling the maximum and minimum radial and vertical velocities.

The model results obtained show that the maximum radial velocity is reached over $0.2 \leq x/D \leq 0.4$. The normalised ($U_r/(Cte\ W_s(D/z_i)^{1/3}) = 1$; *Cte* = 0.33) vertical profiles shown in Figure 6b predict the maximum intensity at a height of (z/z_i) = 0.05 for the convergent branch (from surroundings to the city centre) and at (z/z_i) = 1.05 for the divergent branch (from the city to the surroundings) with an intensity of:

$$U_r/(0.33(D/z_i)^{1/3}) = -0.9 \text{ at } (z/z_i) = 0.05 \text{ and}$$

$$U_r/(0.33\ W_s(D/z_i\ )^{1/3}) = 2.1 \text{ at } (z/z_i) = 1.05$$

The change in surface wind direction with altitude, from convergent to divergent, creates a transition layer with a region of weak flow situated at $(z/z_i) = 0.6$. The radial velocity reaches zero again at the top of the entrainment zone ($z/z_i = 1.15$) where the urban influence ceases to be perceptible.

The vertical velocity at the city centre increases with height from zero at the surface to a maximum at about half the boundary layer height. The normalised ($W/(Cte\ W_s(z_i/D)) = 1$; $Cte = 4.33$) vertical profiles are shown in Figure 6c. The maximum vertical velocity has a value of

$$W/(4.33W_s(z_i/D)) = 1.3 \text{ at } (z/z_i) = 0.68$$

The stability at the top of the UBL prevents this mass of air from rising any further and the vertical velocity becomes zero at a height of $(z/z_i) = 1.18$.

4.2.3 Scaling the vertical profiles of the urban-breeze circulation

A general equation describing the normalised vertical profiles of radial (at $0.2 \leq x/D \leq 0.4$) and vertical velocity (at the city centre $D \leq 0.2$) fields was obtained, as for the temperature, with a least square polynomial fit function:

- The vertical profile of the radial velocity increases with height following the known logarithmic law due to the roughness length imposed at the surface (Section 3). The surface drag starts to be negligible at a height of $(z/z_i) = 0.05$. A quadratic polynomial law is used to describe the vertical profile from this height up to the top of the entrainment layer ($(z/z_i)=1.05$):

$$U_r/(0.33\ W_s(D/z_i)^{1/3}) = 2.94(z/z_i)^2 - 0.28(z/z_i) - 0.86 \text{ for } (0.05 \leq z/z_i \leq 1.05)$$

From that point to the top of the boundary layer (top of the entrainment zone), the horizontal velocity decreases to zero. Only two levels of the model are situated in this thickness and for this reason the deceleration of the horizontal wind is described by a straight line:

$$U_r/(0.33\ W_s(D/z_i)^{1/3}) = -21.23(z/z_i) + 24.41 \text{ for } (1.05 \leq z/z_i \leq 1.15)$$

- A cubic polynomial fit was then used to describe the vertical velocity profile from the surface to the top of the ABL:

$$W/(4.33W_s(z_i/D)) = -2.04(z/z_i)^3 + 0.16(z/z_i)^2 + 2.63(z/z_i) \text{ for } (0 \leq z/z_i \leq 1.18)$$

The general scaling laws obtained are able to reproduce the observed urban-breeze in Toulouse (forcing parameters: zi= 2000 m, D=10000 m and $(H_u-H_r)=0.165$ m K s^{-1}): the intensity of the UHI in surface at the city centre (($UHI_{x=0}$=1.29 K) and at the suburban zone ($UHI_{x=0}$=0.56 K). The horizontal convergent

($Ur_{z=350m}$=-1 m s^{-1}) and divergent ($Ur_{z=1650m}$=1.193 m s^{-1}) branches observed by the aircraft at low levels and at the top of the atmospheric boundary layer. Due to the absence of mean wind in the simplified model, the maximal vertical wind speed ($W_{z=1200m}$=2.28 m s^{-1}) is overestimated respect to the obtained in the realistic run (URB)($W_{z=1200m}$=1-1.5 m s^{-1}).

This study assumed a certain number of simplifications (e.g. non-existent large-scale mean wind, dry atmosphere, circular city) in order to obtain a simplified set of equations that allows a realistic daytime circulation intensity generated by a specified city using only three measurable parameters. Despite the limitations of this idealised approach, these relationships can also be used to quantify the impact on the boundary layer thermodynamics when the city size (D), the meteorological conditions (z_i), and the urban morphology (traduced in a (H_u - H_r) fixed value) change due to urban planning and development.

5. Conclusions

A new approach for scaling the daytime UHI and urban breeze characteristics has been developed in this paper. The external forcing that pilots the urban-breeze circulation development and evolution were identified and used to obtain a set of simple scaling laws describing the urban-breeze features as a function of governing variables. Nocturnal and diurnal differences on the ABL development are pointed out focusing on the importance that the mixed layer is unstable during daytime and there is no notion of mean stability of the atmosphere (as in the countryside nocturnal layer in which forms the nocturnal UHI). The forcing parameters chosen are (i) the size of the city (D), (ii) the height of the inversion layer that tops the mixed layer (z_i), (iii) the difference (urban-rural) of surface heat flux (H_u-H_r).

3D high resolution numerical simulations is the strategy chosen to examine the physical processes dependence on the external forcing involved in the diurnal urban-breeze circulation. A set of simulations performed with the non-hydrostatic Meso-NH atmospheric model, provides a set of urban-breeze circulations forced by an idealized urban environment.

The ability of the idealized model to reproduce accurately the urban breeze in such idealized context is verified by emulating the urban-breeze episode observed in Toulouse the IOP5. The model simulate an surface UHI of 1.5 K, an horizontal wind speed in the convergent branch of the urban breeze reaching a maximum of 2 m s^{-1}, that compares well with the observations for the real city. The 2 m s^{-1} vertical wind speed in the upward motion of the urban breeze over the city is slightly larger than that for a more realistic simulation of the 4th July case (1.5 m s^{-1}).

General laws describing the normalized profiles of temperature and wind fields are obtained with a least-square polynomial fit function:

- daytime UHI maximal intensity: $UHI=17.25\Theta_s$
- daytime UHI surface form (UHI intensity, above the canopy, at different distances from the centre): $UHI/17.25\Theta_s = 1.37(x/D)^3-1.78(x/D)^2-0.58(x/D)+1$
- maximal radial velocity (reached over $0.2 \leq X/D \leq 0.4$ at a height of (z/zi)=0.05 for the convergent branch (from surroundings to the city centre) and at (z/zi)=1.05 for the divergent branch (from the city to the surroundings):

$$U_r/(0.33\ W_s(D/zi)^{1/3}) = -0.9 \text{ at } (z/zi)=0.05$$

$$U_r/(0.33\ W_s(D/zi)^{1/3}) = 2.1 \text{ at } (z/zi)=1.05$$

- minimal radial velocity (over $0.2 \leq X/D \leq 0.4$) is reached at (z/zi)=0.6 (transition layer with a region of weak flow where the surface wind change on direction with altitude, from convergent to the city to divergent). Radial velocity reaches zero again at the top of the entrainment zone ((z/zi)=1.15) where the urban influence cease to be perceptible.
- vertical velocity at the city centre increase with height form zero at the surface to a maximum above the half of the boundary layer height: $W/(4.33W_s(zi/D))=1.3$ at (z/zi)=0.68. The stability at the ABL top stops this mass of air going up and the vertical velocity becomes zero at a height of (z/zi)=1.18
- the vertical profile of radial velocity increase in the first meters with height following the logarithmic law. The surface drag starts to be negligible at a height of (z/zi)=0.05. A quadratic polynomial law is obtained to describe the vertical profile from this height until the top of the entrainment layer ((z/zi)=1.05):

$$U_r/(0.33\ W_s(D/zi)^{1/3}) = 2.94(z/z_i)^2-0.28(z/z_i)-0.86 \text{ between } 0.05 \leq z/zi \leq 1.05$$

From that point to the top of the boundary layer (top of the entrainment zone) the horizontal velocity decrease until zero. The law obtained to describe the deceleration on the horizontal wind is a straight:

$$U_r/(0.33\ W_s(D/zi)^{1/3}) = -21.23(z/z_i)+24.41 \text{ between } 1.05 \leq z/zi \leq 1.15$$

- the vertical velocity profile from the surface to the ABL top is described with a third order polynomial function of parabolic appearance with the centre displaced upwards:

$$W/(4.33W_s(zi/D)) = -2.04(z/z_i)^3+0.16(z/z_i)^2+2.63(z/z_i) \text{ between } 0 \leq z/zi \leq 1.18$$

The scaling laws obtained should be verified with other datasets from future observations or laboratory experiments. The impact of wind strength on the UHI, and the transition from urban breeze to urban plume as the wind increases would be also assessed in further research.

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Figures:

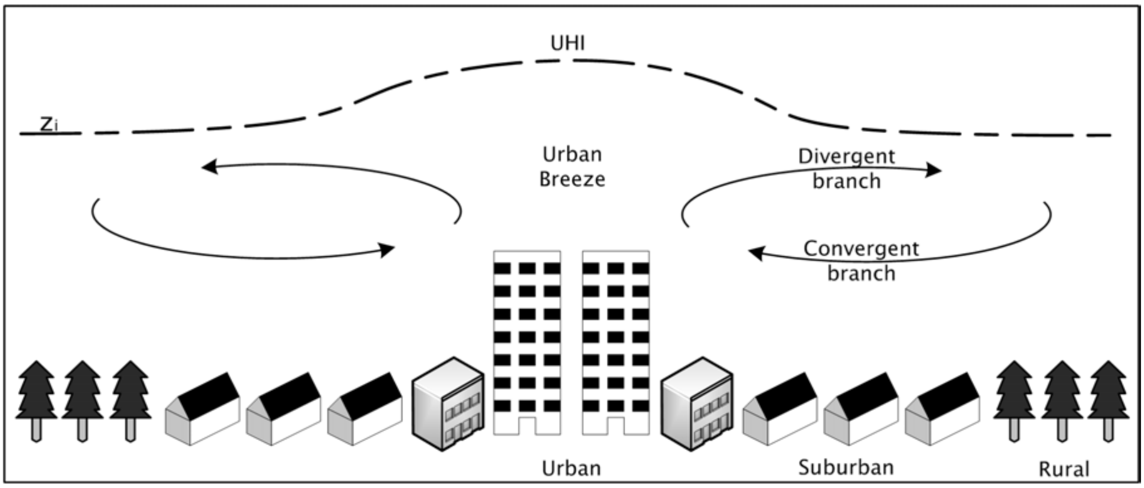

Figure 1: *Schematic representation of the urban boundary layer in the case of the urban-breeze circulation in a hinterland city.*

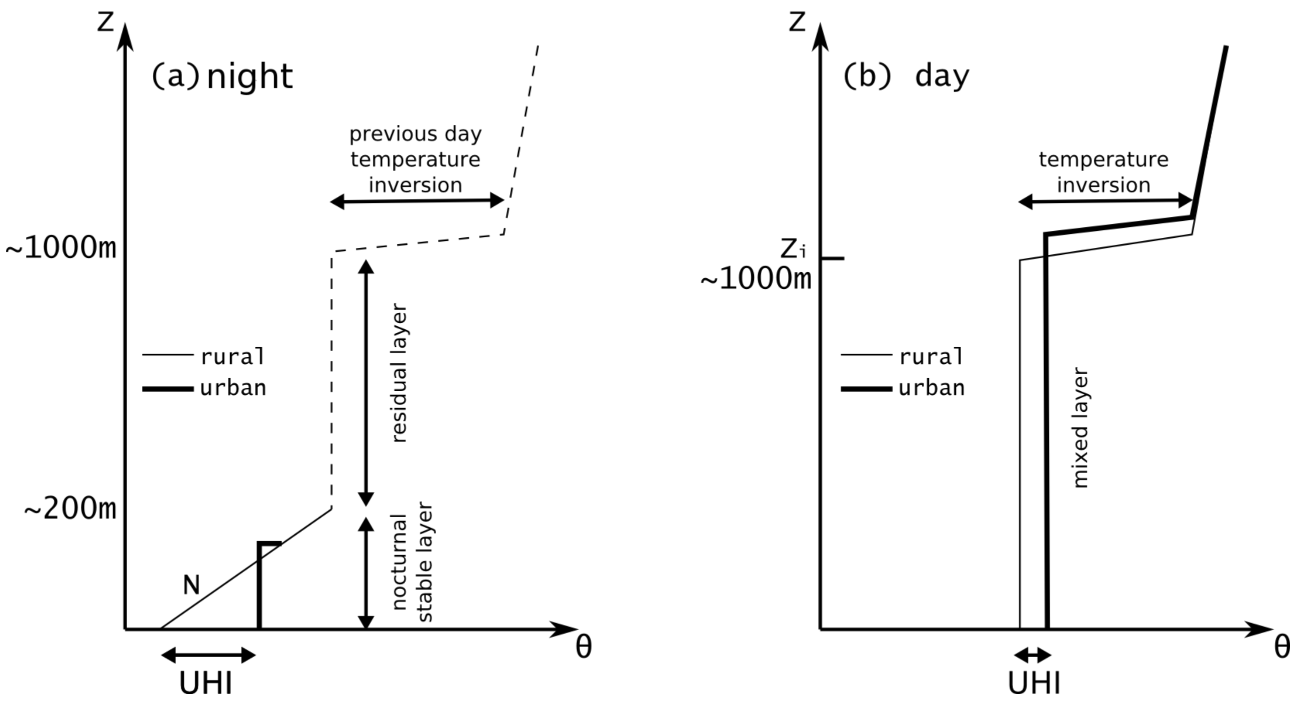

Figure 2: *Schematic representation of the potential temperature profiles associated with the Urban Heat Island (UHI) (a) during the night, and (b) during the day. Thin lines are for rural profiles, bold ones for urban profiles. The dashed line in the night case represents the typical structure of the atmosphere above the nocturnal stable layer.*

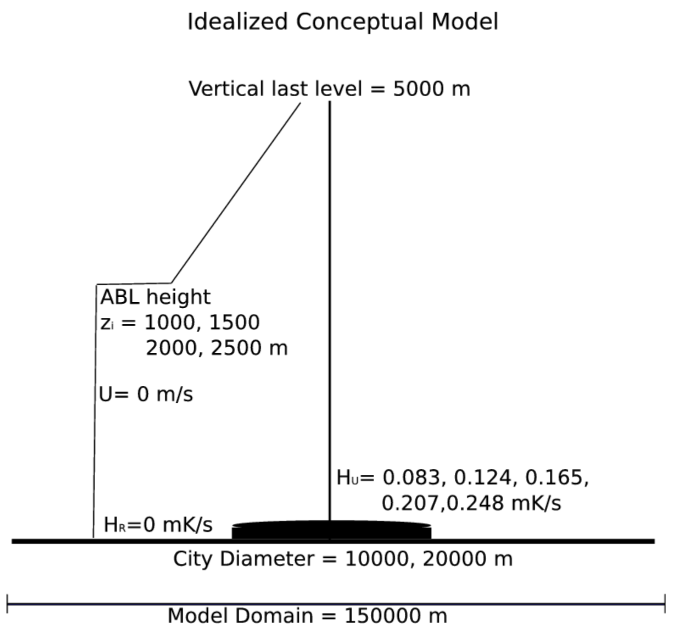

Figure 3: *Conceptual model and numerical simulation characteristics.*

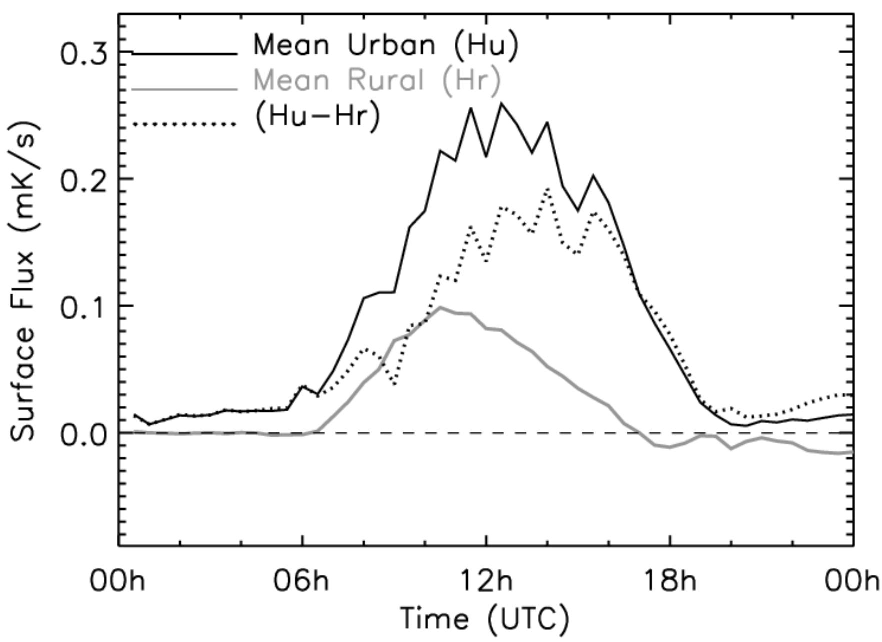

Figure 4: *Observed urban H_u and rural H_r mean summer sensible heat flux. Observed mean summer anomaly (H_u -H_r) fluxes.*

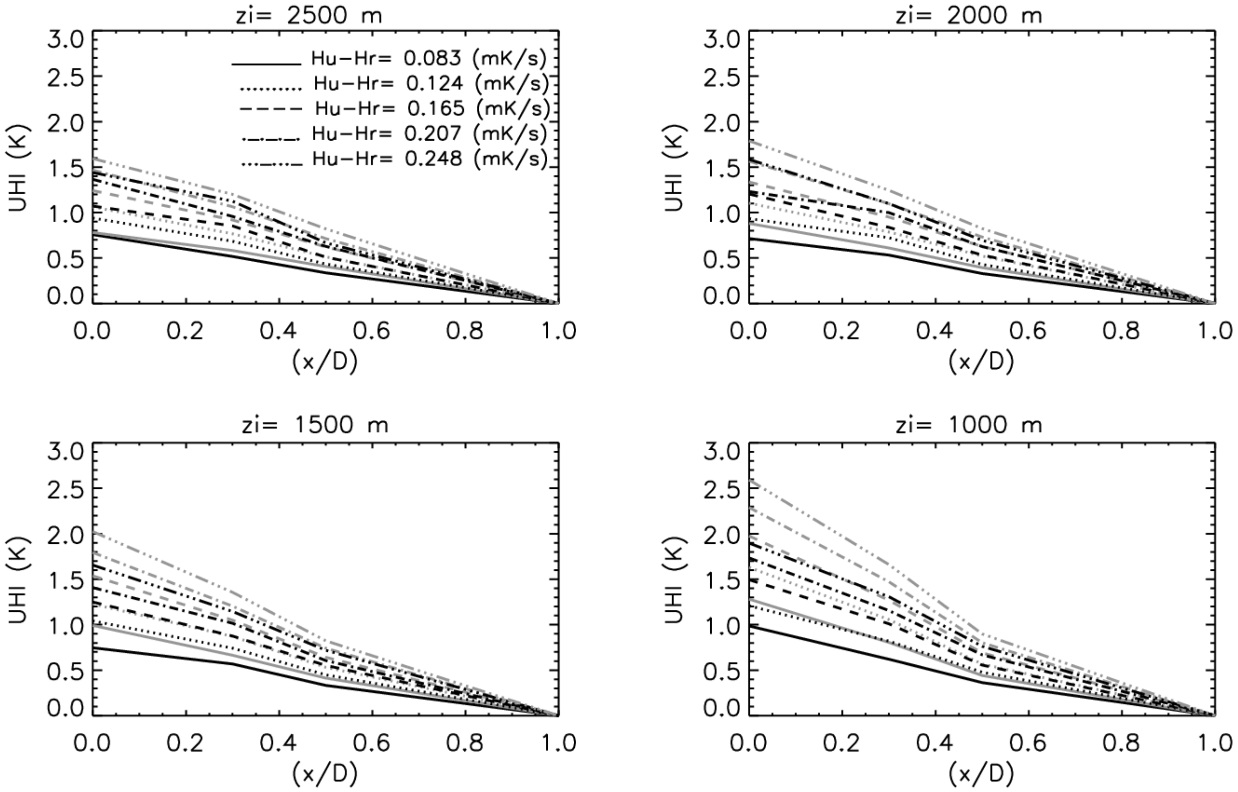

Figure 5: *(a) Horizontal profiles of surface temperature distribution as a function of the nondimensional distance (x/D). The black line corresponds to the D = 10 km and the grey line to the D = 20 km simulations, respectively.*

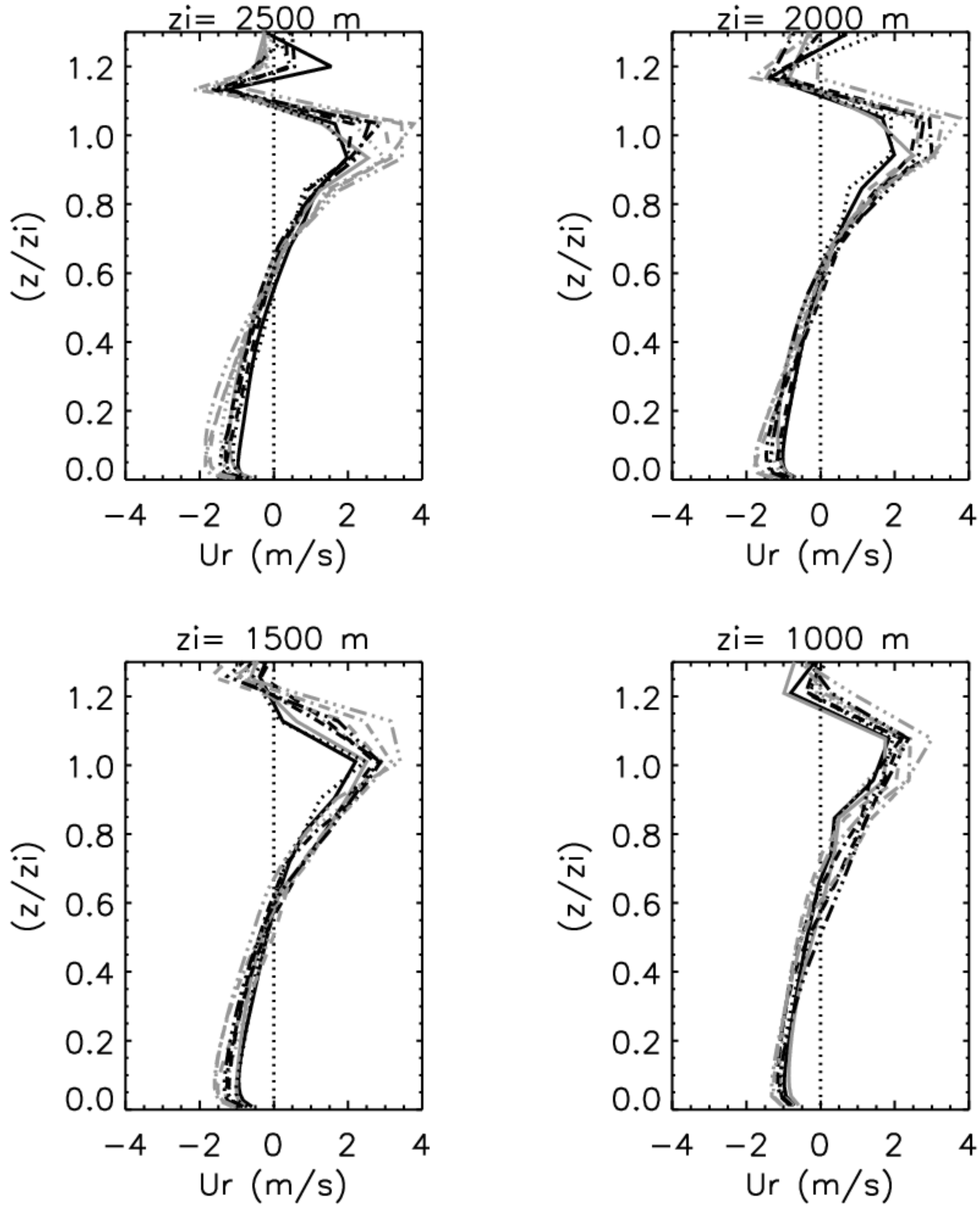

Figure 5: *(b) Vertical profiles of radial velocity as a function of the nondimensional height (z/z_i)* for the different simulations. The black line corresponds to the D = 10 km and the grey line to the D = 20 km simulations, respectively.

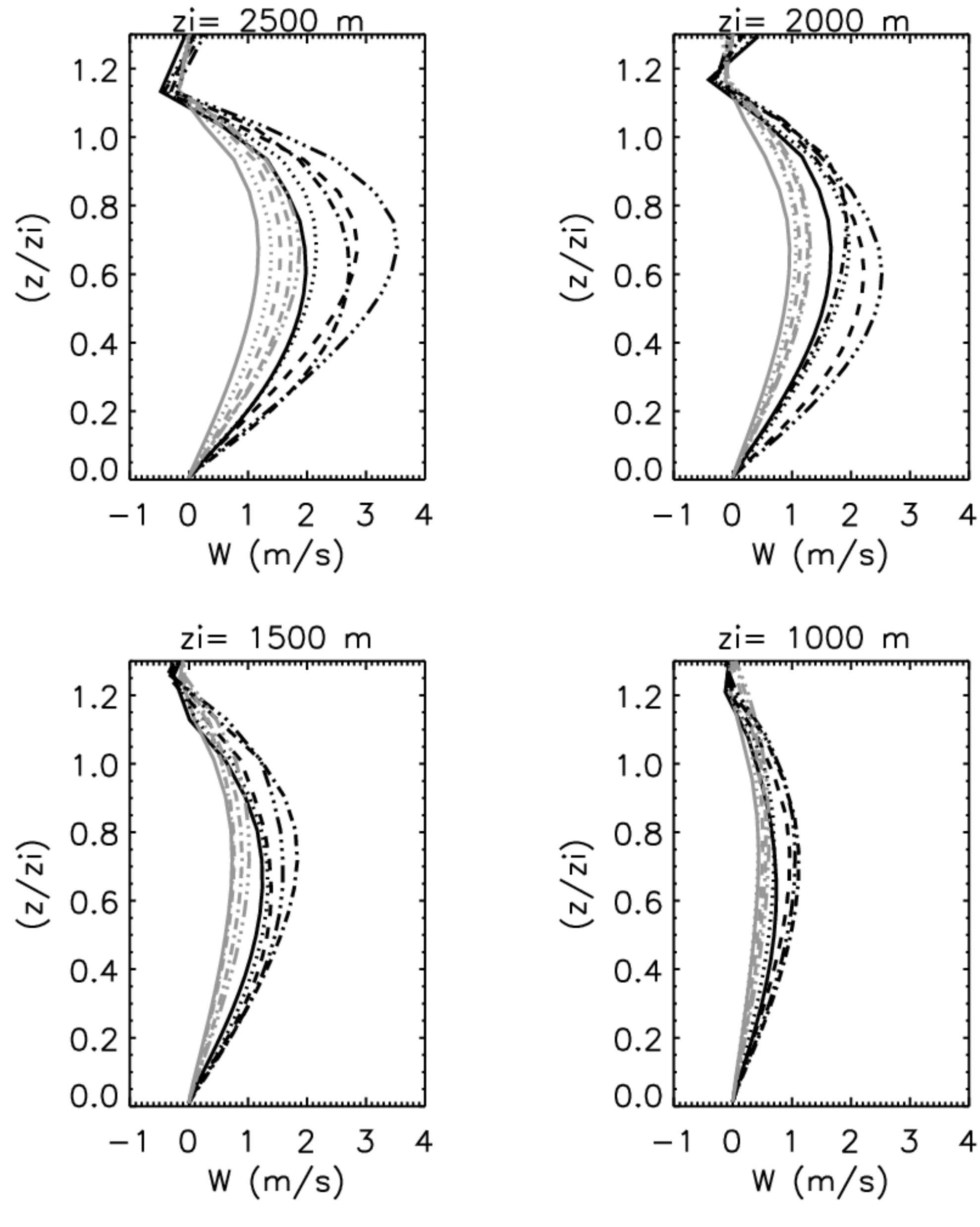

Figure 5: *(c) Vertical profiles of vertical velocity as a function of the nondimensional height* (z/z_i) for the different simulations. The black line corresponds to the D = 10 km and the grey line to the D = 20 km simulations, respectively.

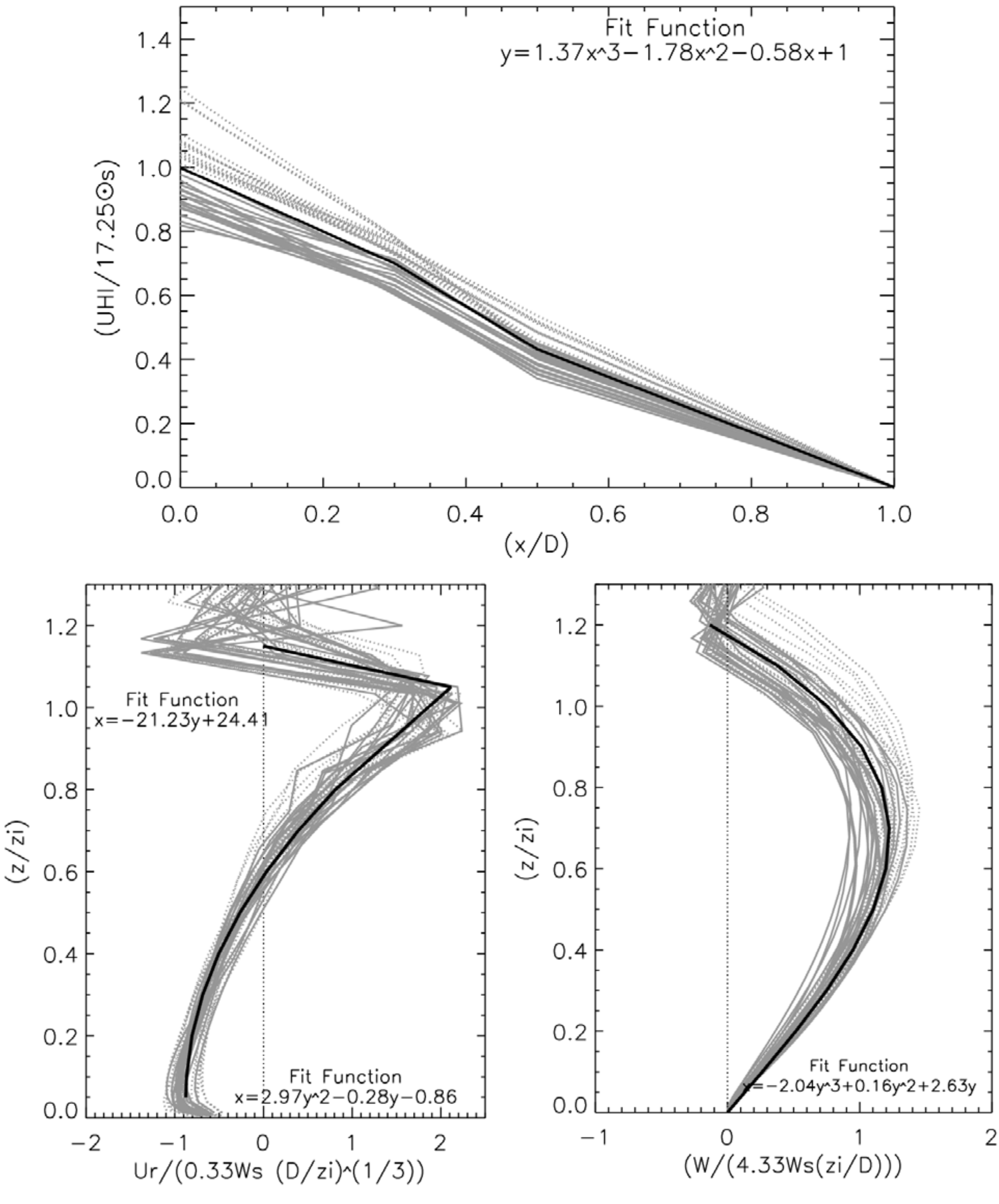

Figure 6a: *Normalised horizontal profiles of surface temperature distribution (12 m of height) from the centre of the domain (top), radial velocity (down left) and vertical velocity (down right). The continuous grey line corresponds to the D = 10 km simulation, the dotted grey line to the D = 20 km simulation, and the black lines represent the best least square polynomial fit.*

Final Conclusions

This manuscript presents different approaches (observational, numerical simulations and theoretical) applied to the study of the *Urban-Breeze Circulation,* central topic of this thesis*,* created in presence of a daytime *Urban Heat Island,* under cloudles skies when regional winds are very light. The different approaches are combined to advance in the knowledge of this mesoscale phenomenon postulated theorically in analogy with the sea-breeze circulation, simulated with numerical models by some authors but only partially observed before this study (St-Louis, 1978).

The experimental campaign CAPITOUL dedicated to the study of the urban climate in Toulouse. The field campaign objectives were to quantify the effects and causes of the interactions between the urban surface, the development and 3D-structure of the urban boundary layer and of urban aerosols, at the scale of the city down to the scale of the districts. The size and geographic situation of Toulouse far from areas influenced by mountain or sea circulations makes the dataset obtained during CAPITOUL a valuable support to study the urban influence on the atmospheric boundary layer and in particular the urban-breeze circulation. The principal scientific results about the urban-breeze are presented in three papers.

The experimental and numerical studies focus on the IOP5 of the CAPITOUL experiment analysing an urban-breeze situation observed over Toulouse the 4th July, 2004. The meteorological context of the period is described using ground weather stations, wind profilers, radio soundings and aircraft data. High resolution numerical simulations with the atmospheric model Meso-NH coupled with the urban surface scheme TEB are used to evidence and study the 3-D mesoscale urban effects difficult to observe with an experimental deployment. Both approaches have allowed the study of the SEB components and the vertical ABL structure relative roles in the development of the low-level airflow convergence towards the city.

The main results obtained through observations and simulations are a daytime +1°C heat island able to generate an urban-breeze over Toulouse. The breeze observed by the aircraft between 12.30 to 15.20 UTC is characterized by near surface convergence towards the city with an intensity of 1-2 m s^{-1} and with an horizontal extension in the axis SE-NW which is 2 to 3 times bigger than the size of the city and a divergent return current in upper levels at the top of the ABL, reaching 2 m s^{-1}. The urban-breeze circulation grows in intensity during the afternoon and is able to dominate the flow pattern.

The dynamical perturbation on the ABL due to the roughness of urban covers was estimated during the morning when the UHI intensity is minimal assuming that only mechanical processes play a major role in the perturbation of the wind field. The deceleration of the large-scale wind due to the roughness of Toulouse is of 1.5 m s^{-1} at the surface and decreases fast on the vertical until a height of 100 m.

The last paper presents an original scaling of the daytime UHI and urban-breeze characteristics where a theoretical approach complete this urban-breeze features study. The external forcing that pilots the urban-breeze circulation development and evolution are identified and used to obtain a set of simple scaling laws describing the urban-breeze features in function of governing variables. Night-time and daytime differences on the ABL development are pointed out focusing on the importance that the mixed layer is unstable during daytime and there is no notion of mean stability of the atmosphere. The forcing parameters chosen are the size of the city (D), the height of the inversion layer that tops the mixed layer (z_i), the difference (urban-rural) of surface heat flux (H_u-H_r).

3D high resolution numerical simulations is the strategy chosen to examine the physical processes dependence on the external forcing involved in the daytime urban-breeze circulation. A set of simulations performed with the non-hydrostatic Meso-NH atmospheric model, provided a set of urban-breeze circulations forced by an idealized urban environment. The ability of the idealized model to reproduce accurately the urban breeze in such idealized context is verified by emulating with pertinent D, zi and (H_u-H_r) parameters of the urban-breeze episode observed in Toulouse the IOP5. Overall the simplifications made here to represent the physics of the UHI and urban breeze seem valid.

General laws describing the normalized profiles of temperature and wind fields are obtained with a least-square polynomial fit function for the daytime UHI maximal intensity:

$$UHI=17.25\Theta_s \; ; \; \Theta_s = (H_u - H_r)^{2/3}(\beta z_i)^{-1/3}$$

and for the daytime UHI surface form:

$$UHI/17.2\Theta_s=1.37(x/D)^3-1.78(x/D)^2-0.58(x/D)+1.$$

Equivalent laws were obtained for the radial and vertical velocities of the city. The general scaling laws are able to reproduce the observed urban-breeze in Toulouse.

Perspectives

The work presented here offers quantitative estimations about the strength and horizontal and vertical extension of this local circulation in a real city (Toulouse) as well as general laws describing the urban-breeze features for any location (always keeping in mind the limits imposed by the idealized conditions (non-existent large scale mean wind, dry atmosphere, circular city...)) in function of three measurable governing variables (D, z_i and H_u-H_r). From this point on some questions remains still opened:

- The urban-breeze circulation observed during the IOP5 was analysed from a point of view of the ABL energetics and thermodynamics. The study of the breeze impact on the air quality for this day waits to be done. A complete dataset of aerosols and CO_2 measures is available for this IOP. Data from the CAPITOUL campaign are available to the scientific community on the campaign web site (http://medias.cnrs.fr/capitoul).

- The amplitude of the diurnal cycle of surface temperature in Toulouse during wintertime under cloudless anticyclonic meteorological situation is similar to the IOP5 summertime case (*Hidalgo et al.*, 2006). The major differences are the absence of a heat island during the daytime and the absence of an urban-breeze circulation for this winter day. The energy balance in the city centre shows well the difference of external forcing between summertime and wintertime. However the atmospheric response near the ground in terms of sensible flux present very similar values for both cases (remains positive during the night and have similar cycle during the day). In winter the lack of solar energy is replaced by the anthropogenic heating at the surface. The seasonal differences in terms of SEB, temperature and atmospheric stability impacts on the ABL dynamics are interesting for future research. Daytime and nigh-time differences in terms of vertical UHI structure (impact of the “cross-over effect” over the city during the night) should be also assessed in future research.

- The scaling laws obtained should be verified with other datasets from future observations or laboratory experiments.

- The impact of wind strength on the UHI, and the transition from urban breeze to urban plume as the wind increases would be assessed in further research.

The scaling laws can be used to quantify the impact on the BL thermodynamics when the: city size (D), the meteorological conditions (z_i) and the urban morphology (traduced in a H_u-H_r fixed value) changes throughout the time due to the city evolution or by means of urban planning.

Conclusions Finales

Ce manuscrit présente trois différentes approches (experimentale, à l'aide de simulations numériques, et théorique) appliquées à l'étude de la *circulation de brise urbaine diurne*, thème central de cette thèse. Les différentes approches sont combinées pour avancer dans la connaissance de ce phénomène de méso-échelle postulé théoriquement par analogie avec la circulation de brise de mer, simulée à l'aide de modèles numériques par quelques auteurs mais seulement partiellement observée (St-Louis, 1978) avant cette étude.

La campagne expérimentale CAPITOUL a été consacrée à l'étude du climat urbain à Toulouse. Les objectifs de cette campagne ont été de mesurer les effets et les causes des interactions entre la surface urbaine, le développement et la structure tridimensionnelle de la couche limite urbaine et des aérosols urbains, de l'échelle de la ville à l'échelle des quartiers. La taille et la situation géographique de Toulouse, loin des zones influencées par des circulations de montagne ou de mer, fait de l'ensemble de données obtenues pendant CAPITOUL un support précieux pour l'étude de l'influence urbaine sur la couche limite atmosphérique et en particulier la circulation de brise urbaine. Les principaux résultats scientifiques au sujet de la brise urbaine sont présentés dans trois articles.

Les études expérimentales et numériques se sont focalisées sur l'IOP5 de la campagne CAPITOUL. Une situation de brise urbaine sur Toulouse le 4 juillet, 2004 est analysé. Le contexte météorologique de la période est décrit en utilisant les stations au sol, des profileurs de vent, des radiosondages et des données d'avion. Les simulations numériques à haute résolution avec le modèle atmosphérique à méso-échelle Meso-NH couplées au modèle de surface urbain TEB sont employées pour mettre en évidence les effets urbains à méso-échelle 3-D difficiles à observer avec un dispositif expérimentale.

Ces deux approches ont permis l'étude de l'importance relative des composantes du bilan d'énergie de surface et de la structure verticale de la couche limite dans le développement de la convergence de surface vers la ville. Il est mis en évidence l'importance d'accompagner les mesures de surface avec des observations de la structure verticale de la couche limite atmosphérique pour décrire correctement le transport horizontal dans les couches inférieures.

Les principaux résultats obtenus par des observations sont les suivants: l'îlot de chaleur diurne de +1 °C est capable de produire une circulation de brise urbaine sur la ville de Toulouse. Le gradient de la température commence à 12.00 UTC. La brise observée grâce aux données d'avion entre 12.30 à 15.30 UTC est caractérisée par:

- Une convergence vers la ville proche de la surface avec une intensité de 1 à 2 m s^{-1} et une extension horizontale sur l'axe SE-NW qui est 2 à 3 fois plus importante que la taille de la ville.
- Un courant de retour divergent dans les niveaux supérieurs de la couche limite, atteignant 2 m s^{-1} à 13.00 UTC.

La brise urbaine se développe en intensité pendant l'après-midi et est capable de dominer l'écoulement.

La perturbation dynamique de la couche limite dûe à la rugosité des surfaces urbaines a été evaluée pendant la matinée. quand l'îlot de chaleur a une intensité minimale et est analysé en supposant que seulement les processus mécaniques ont un rôle majeur dans la perturbation du champ vent. La décélération du vent à grande échelle dû à la rugosité de Toulouse est de 1.5 m s^{-1} en surface et diminue rapidement à la verticale jusqu'à une altitude de 110 m.

Le dernier article présente une étude originale des caractéristiques de l'îlot de chaleur diurne et de la brise urbaine d'un point de vue théorique. Les forçages externes qui pilotent le développement, l'évolution de la brise urbaine sont identifiés et utilisés pour obtenir une série de lois décrivant les caractéristiques de la brise en fonction de ces variables. Les différences dans le développement de la couche limite en conditions nocturnes et diurnes sont analysées en se focalisant sur l'importance du fait que la couche limite mélangée est instable dans la journée et qu'il n'y a pas de notion d'instabilité moyenne de l'atmosphère (tout comme pour la couche nocturne en zone rurale, dans laquelle l'îlot de chaleur est formé. Les paramètres de forçage choisis sont la taille de la ville (D), l'altitude de la couche d'inversion au somment de la couche mélangée (z_i), et la différence des flux de chaleur sensible entre zones urbaine et rurale (H_u-H_r).

Des simulations numériques tridimensionnelles de haute résolution (500m) est la stratégie choisie pour examiner la dépendance des forçages externes impliqués dans la circulation de brise. Un ensemble de simulations, effectuées avec le modèle Meso-NH, fournit un ensemble de circulations de brise urbaine forcées par un environnement urbain idéalisé. Des lois générales décrivant les profils normalisés des champs de la température et de vent sont obtenues avec une fonction polynômique par la méthode des moindres carrés.

Annexe 1

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

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Abstract: 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 wintertime, 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_6 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.

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 (Cachier *et al.*, 2005; Liousse *et al.*, 2005;

Cousin *et al.*, 2005; Mallet *et al.*, 2005 et 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 a 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 (Pigeon *et al.*, 2006; Bastin and Drobinski 2005; Lemonsu *et al.*, 2006a; Lemonsu *et al.*, 2006b). 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 (SF6) 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 Particle Interactions in Toulouse Urban Layer (CAPITOUL) experiment. Section 1.2 presents the objectives, section 1.3 outlines the experimental network and Section 1.4 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, ΔQs is the net energy storage uptake by or released from surfaces (buildings, roads, soils) and ΔQ_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 (1km) 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 modifies 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:

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

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 micro-physical 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 reduced 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 CAPITOUL 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 Sureté Nucléaire) are involved in the national crisis cell when an accidental release occurs. The CAPITOUL 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 availability of a complete description of the urban surface and boundary layer thermodynamics, together with SF6 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 CAPITOUL 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 20km across and encompasses 0.9M inhabitants. A European city of this size is considered likely to generate an urban heat island of about 8 degrees (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 km², is relatively homogeneous in terms the building height (approximately 20 m) and construction materials (red brick walls and tile roofs) (Figure 1). These characteristics suggest it favours the study of turbulent transport flows for a dense downtown area.
- 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'aérologie, 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 Figure 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.

3.2 Year-long measurements

(I) 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 Figure 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 (Figure 4a). 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 hr^{-1} , 38.5 m for winds 70-90 km hr^{-1}, and 26 m winds > 90 km hr^{-1} 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 (Figure 4b) 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 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 *et al.*, 2008, *this issue*) was established from filters in two particle size ranges (PM10 and PM 2.5). 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 PM2.5 and PM10 made by the ORAMIP local air quality agency (http://www.ORAMIP.org) provide further data from many other sites in Tolouse that extend the measurements made here.

(II) 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 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.

(III) 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 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 minutes in order to calculate the aerosol optical depth (AOD) and its spectral dependence (Angstrôm 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.

(IV) 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.

(V) 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.

(VI) 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.

(VII) 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 infra-red wavelengths (Briottet, 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 (3-14µm), 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 (Lachérade *et al.*, 2005).

Furthermore, to achieve a complete material classification over an entire urban area, an airborne campaign was conducted using a high spatial (20cm) 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 (Lachérade *et al.*, 2008, *this issue*).

3.3 Intensive Observation Periods

(I) 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 and Masson (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 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 70m.

Aerosol measurements were also performed on-board 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 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 simultaneous 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).

(II) 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 (PM1, PM2.5 and PM10) 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 µm, 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 (figure 5).

During the summer IOP (25 June - 10 July), a mobile laboratory instrumented for measurements of gases (CO, O_3, 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.

(III) 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.

(IV) 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 centre), and ground truth surface temperature measurements (see 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.

(VI) 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 SF6 releases at ground level monitored by both surface and airborne measurements (Lac *et al.*, 2008, *this issue*). The SF6 was released at ground level during the period between 1h to 3h, in a suburban area (Fig.6.a). Sampling took place at ground-level (20cm) 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.6.b). 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_6 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 (ΔQ_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 meaningless value for winter. This is because another source of energy

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 figure 10). This suggest that at the seasonal scale and for moderate climate cities, the energy partitioning variability is primarily dependant on vegetation evapotransipiration 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. ΔQ_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 Figure 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.

The energy balance measurements were used to validate the numerical 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 Figure 8 and compared with the observations from the tower. The diurnal cycle of the sensible heat flux is well reproduced, with the correct intensity during the day. During the night, observations show a significant positive Q_H (50 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 W m^{-2}.

The simulation of the residual is correct (-95 W m^{-2} observed, -92 W m^{-2} modelled, see also bottom panel of Figure 8) and the modelling of heating in TEB produces an anthropogenic heat flux as large as 87 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 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 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 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 ΔQ_S) produces upward sensible heat flux, forming a slightly convective layer typically 100 m to 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 phenomenon: 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 6^{th} 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 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 PM2.5 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 (figure 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 us to estimate a daily direct radiative forcing for the period of June-July 2004 using a radiative transfer model (Roger *et al.*, 2006, Mallet *et al.*, 2005). 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 K/day during daytime.

Particle concentrations in the 0. 3 – 2.0 µm 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 et 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° and 60°. 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 km² with the Gastellu-Etchegorry (2008, *this issue*) model.

4.7 Evaluation of dispersion modelling

Despite the fact that 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 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_6 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 south-west 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 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 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 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_6 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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	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)												

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.*

IOP number	1	2	3	4	5	I RT1	I RT2	IRT3	6	7	8	9	10	11	12	13	14 IRT4
Objective(s)	UBL	UBL SF6	UBL SF6	UB L	UB L SF6	IRT	IRT	IRT	Fog	Fog	UB L	Fog	Fog	UBL Fog	UBL	UBL	UBL IRT
date	2/3 Marc h 2004	9/10 Mar ch 2004	26/2 7 June 2004	30 Jun e 200 4	1 to4 July 200 4	15 July 200 4	29 S ept 200 4	3 /4 Oct. 2004	23/2 4 Nov. 2 004	26 N ov. 2 004	13 D ec. 2 004	5 Janv . 2 005	7 Janv . 2 005	14 Janv. 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 SF6 Aicraft SF6																	
Daytime IRT flights Nighttime IRT flight Hand-held IRT																	

Table 2. *List of Intensive Observing Periods (IOP), describing the main objective of the IOP (UBL: UBL*

structure; IRT: Infra-Red surface anisotropy; Fog: urban fog; SF6: dispersion study), as well as the extra instrumentation used. Grey indicates periods when instrumentation are operational and data validated.

	Turbulence	**Radiation**	**Temperature**	**Humidity**	**Particules**	**Precipitation**
City center (mast top)	Sonic Gill HS 50 Licor 7500 Grimm 1.108	CNR1 Kipp et 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 81000					
City center Pomme street boom	Sonic Young 81000 Licor 7500		P1000 Ohm		Grimm 1.108	
City center Alsace street boom	Sonic Young 81000 Licor 7500				Grimm 1.108	
Suburban site Université Paul Sabatier	Sonic Metek USA1 Krypton KH20	Schenk	PT100 Ohm	HMP45 Vaisala		
Rural site Le Fauga	Aerodynamical method	Schenk	PT1000 Ohm	HMP45 Vaisala		Qualimetrics
Rural site Saint Sardos	Sonic Gill R2 Krypton KH20	CNR1 Kipp and Zonen	PT1000 Ohm	HMP45 Vaisala		Qualimetrics

Table 3. *Summary of surface energy balance measurements*

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

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

SEB QUANTITY	Q* (Wm^{-2})	QF(Wm^{-2})	QH(Wm^{-2})	QE (Wm^{-2})	QH/Q*	QE/Q*	QH/(Q*+QF)	QE/(Q*+QF)
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

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.*

	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

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.*

List of figures

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

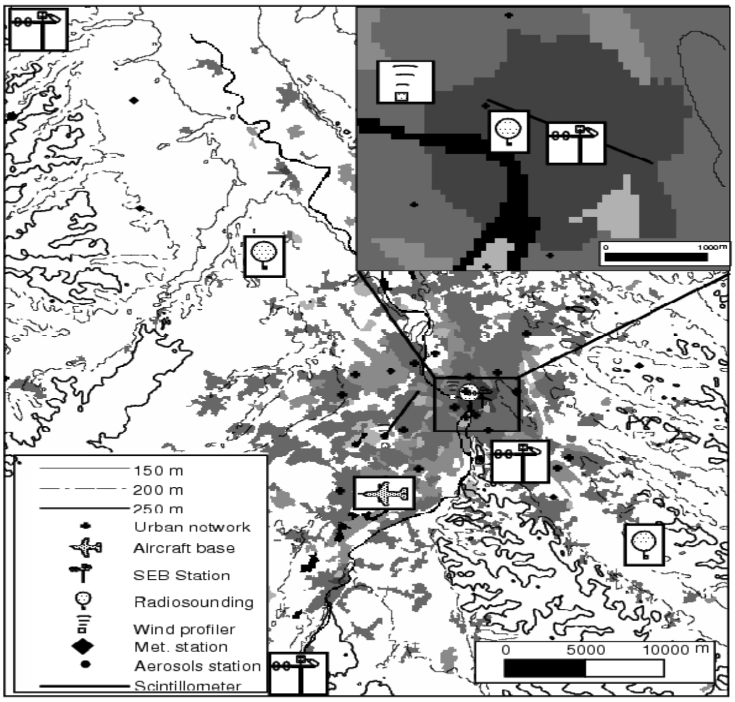

Figure 2: *Overview of the CAPITOUL experimental network in and around the city of Toulouse*

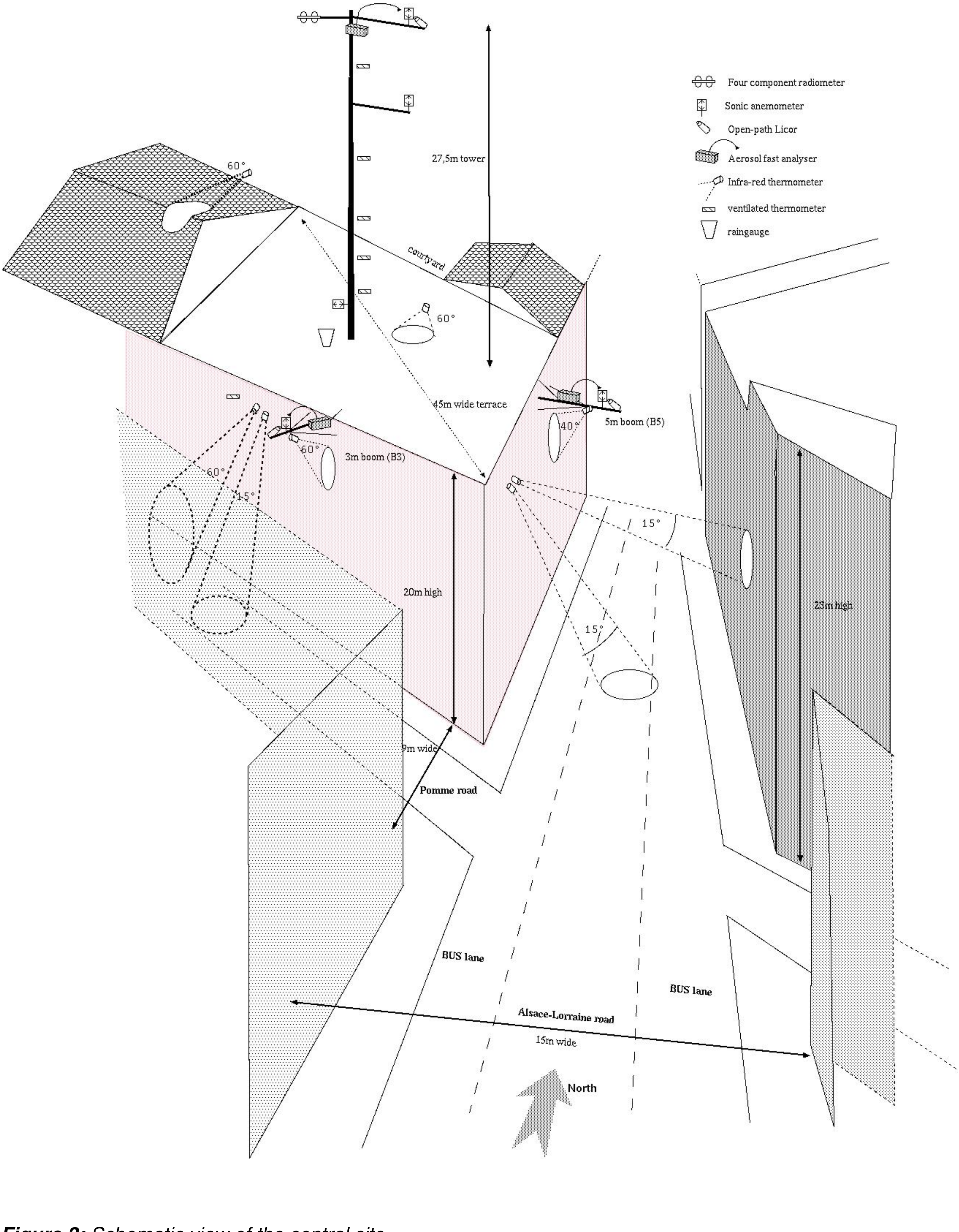

Figure 3: *Schematic view of the central site*

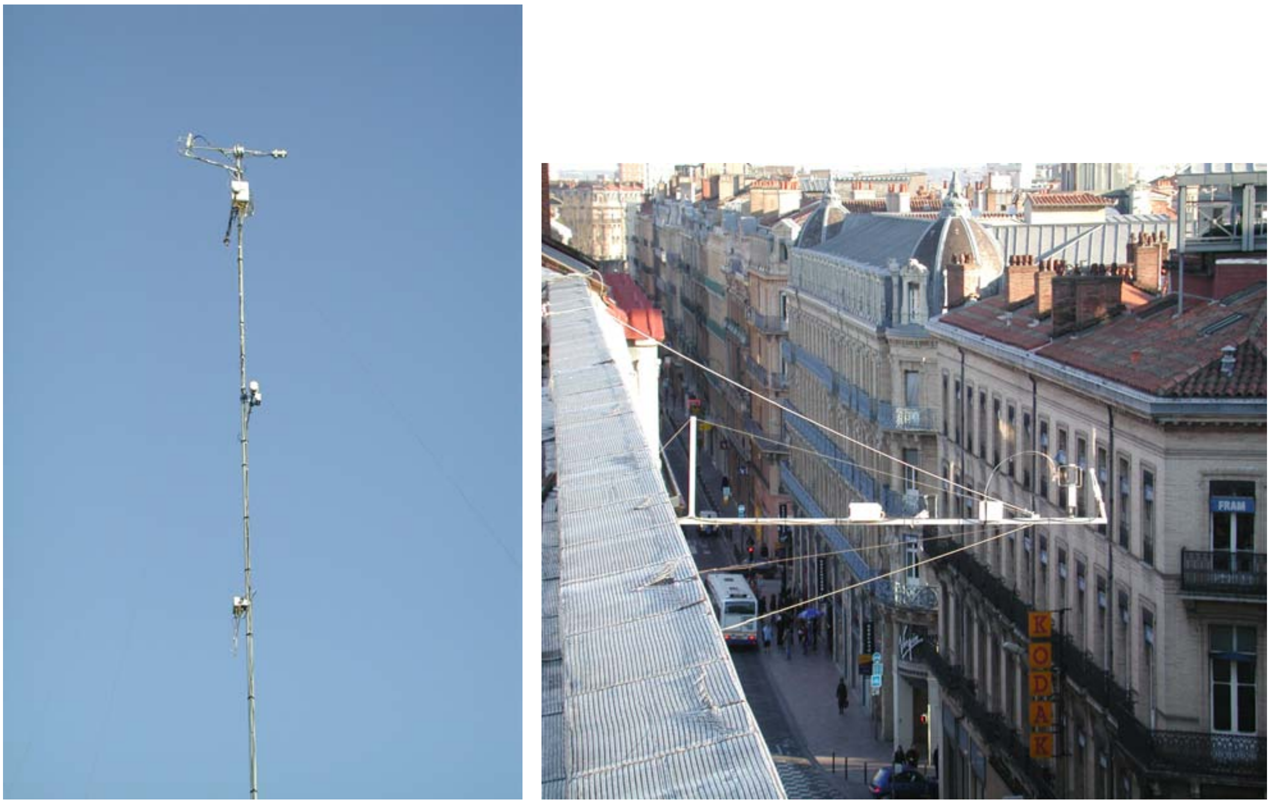

Figure 4: *Left : the pneumatic tower for surface energy balance observations; Right: 5 m turbulence-aerosol measurement boom at the top of Alsace-Lorraine street canyon.*

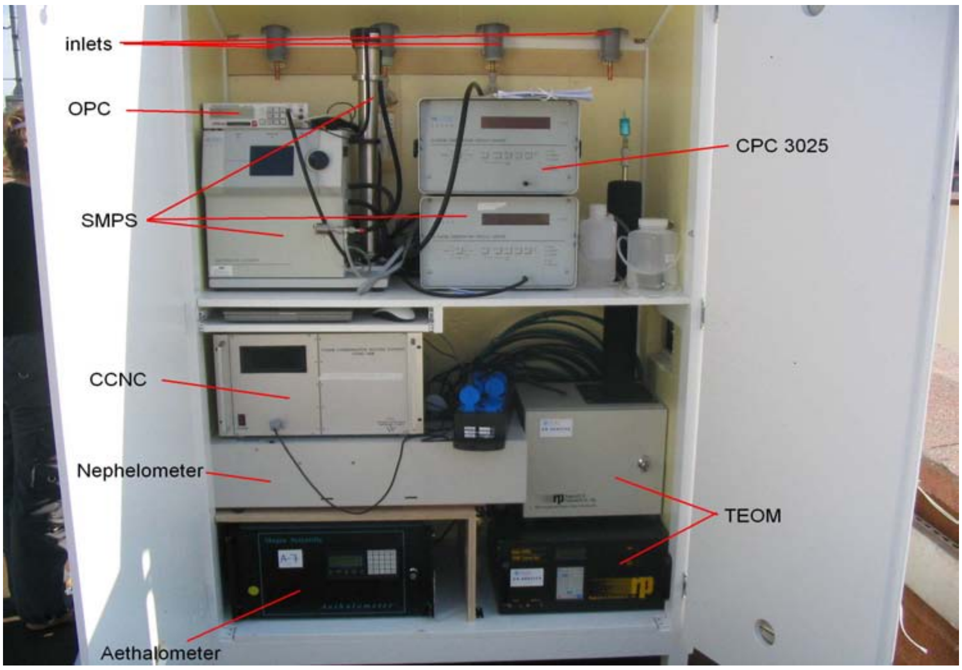

Figure 5: *Instruments to monitor the physical and radiative properties of the aerosols during CAPITOUL IOPs on the roof of the Toulouse central Post Office (see text for details).*

Figure 6: *Instruments to measure SF_6 dispersion**:** a: The laboratory van equipped with a telescopic 10 m mast. SF_6 is released at 2m50 of height (seen behind the van). b: Ground sampling with a drop by drop system. c: Aircraft rack including 30 gas syringes.*

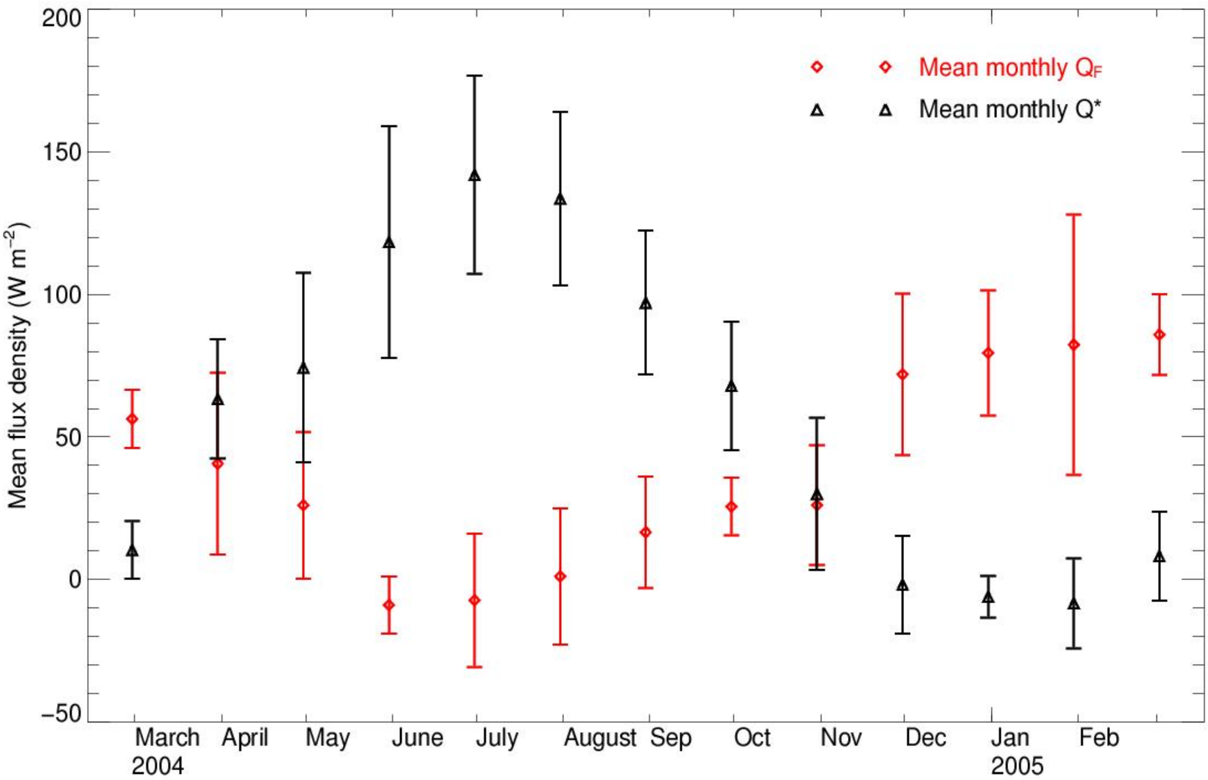

Figure 7*: Annual cycle of net radiation (black) measured at the top of the central site tower, and of anthropogenic heat flux (red), estimated from the integrated residual method. Vertical bars indicate day-to-day variability.*

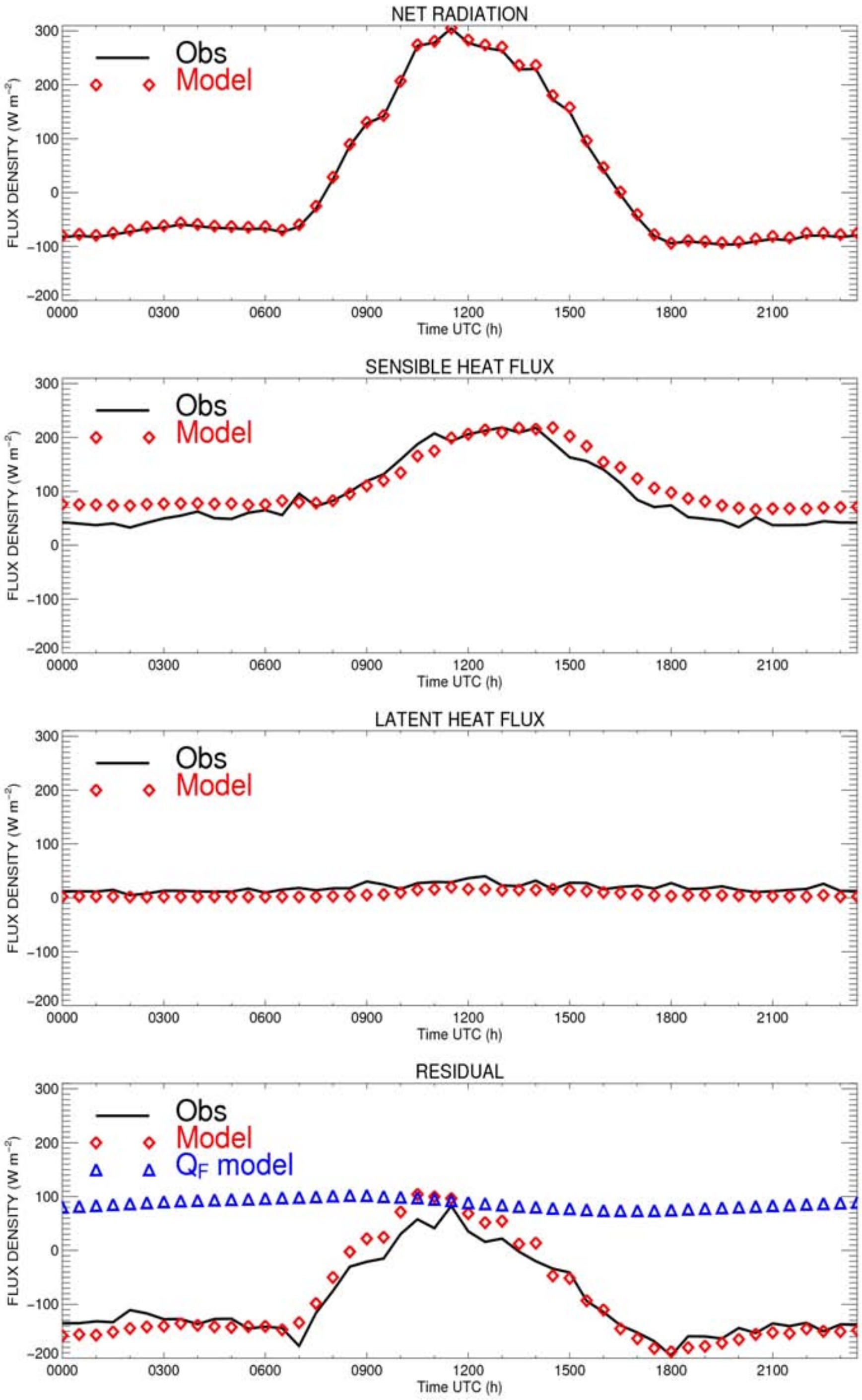

Figure 8: *Comparison between TEB simulated and observed components of the surface energy balance. Mean diurnal cycle for the period 20-28 February 2005.*

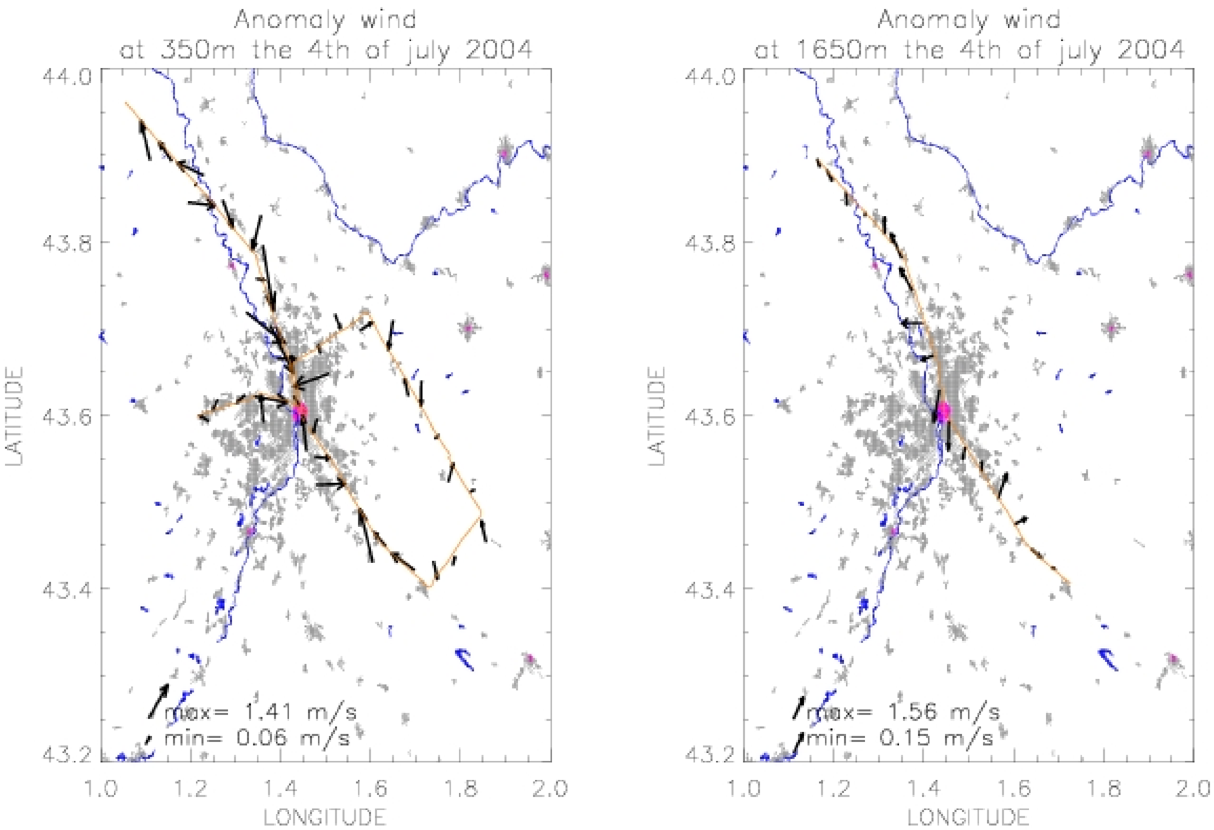

Figure 9: *Urban breeze during the afternoon of the 4th of July, 2004. Left: aircraft wind anomaly in the lower boundary layer (convergence). Right: aircraft wind anomaly in the entrainment zone (divergence).*

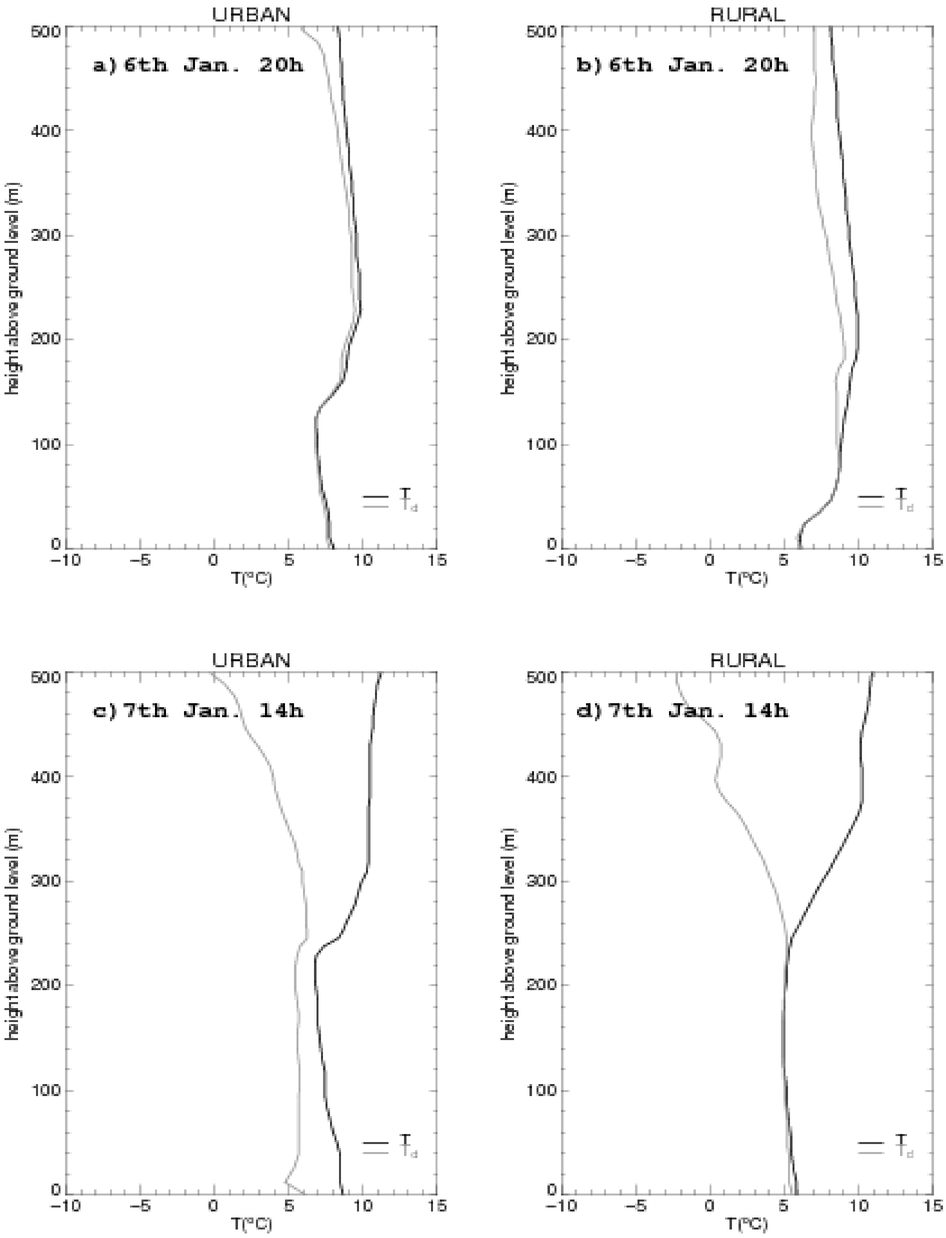

Figure 10: *Urban fog evolution: a) urban and b) rural radiosoundings on the evening of 6th of January, 2005. c) urban and d) rural radiosoundings in the afternoon of 7 January 2005. Black line is temperature, grey line is dew point temperature.*

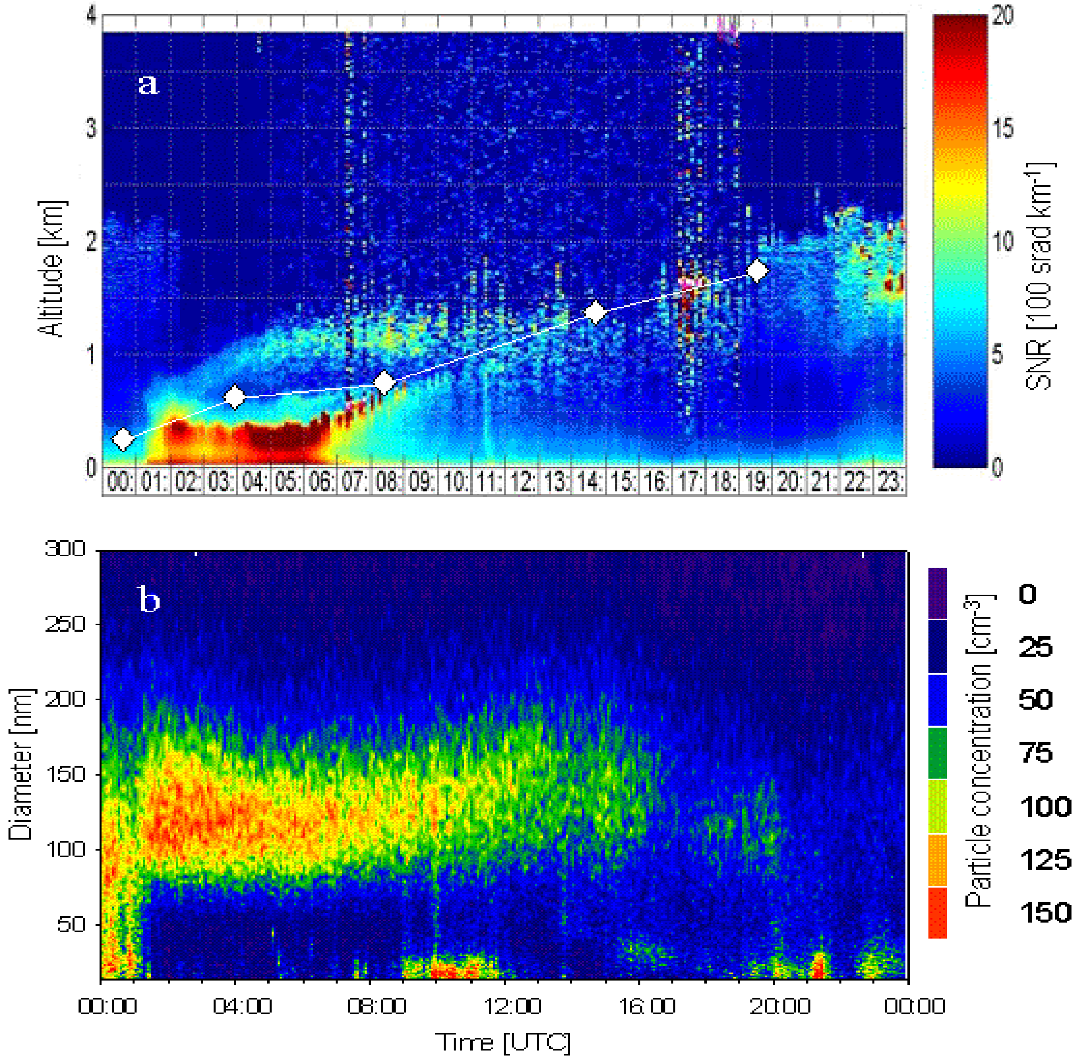

Figure 11: *(a) Evolution of the boundary layer on the 27th June 2004, observed by the VAISSALA modified ceilometer (color) and the radiosoundings (white diamonds). (b) Evolution of aerosol particles concentration per size class on the same day.*

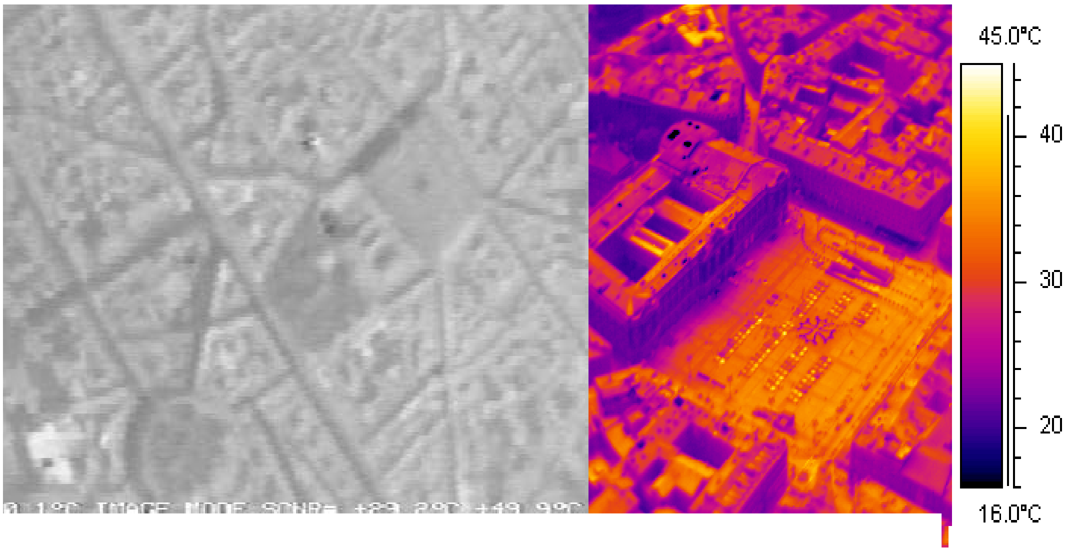

Figure 12: *Examples of thermal images acquired over the Capitol square with the two TIR cameras: INFRAMETRICS M740, 2004 October 4, 11:11:51 UT (left) and FLIR SC2000, 2004 July 11, 13:47:23 UT (right).*

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PhD, Thesis

AN OBSERVATIONAL, NUMERICAL AND THEORETICAL APPROACH TO THE DAYTIME URBAN-BREEZE CIRCULATION IN INLAND CITIES

Julia HIDALGO

Abstract:

From a social, economical and meteorological point of view, the urban environment is a complex system which deserves the attention of a multidisciplinary scientific community. The city modifies the local and regional weather. The city modifies the surface energy-balance and the composition of the atmosphere compared to the surrounding 'natural' terrains, temperature showing the most obvious alteration (the well-known urban heat island). The impact on the flow dynamics due to the surface heterogeneity, larger roughness and horizontal temperature gradients between urban and rural environments is more difficult to observe but is important in air quality management, structures design and urban comfort.

This study focuses on the local circulation created in presence of a daytime urban heat island, under cloudless skies when regional winds are very light, called urban-breeze circulation. Different approaches are combined to advance in the knowledge of this mesoscale phenomenon: An experimental study of the urban-breeze using observational data from the CAPITOUL campaign carried out in Toulouse between February 2004 and March 2005. A numerical approach using high resolution numerical simulations performed with the non-hydrostatic atmospheric model Meso-NH coupled with the urban surface scheme TEB, allows to quantify the unmeasured 3-D mesoscale urban effects. Both approaches allowed to obtain the intensity and extension of the convergent and divergent branches of breeze, the vertical convective velocities and to quantify the perturbation on the temperature and moisture fields. Finally, a theoretical study of the thermodynamic profiles of temperature and wind using 3D high resolution numerical simulations is the strategy chosen to examine the physical processes dependence on the external forcing involved in the daytime urban-breeze circulation. A set of simple scaling laws describing the urban-breeze features as a function of a selected governing variables is presented.

Keywords: Urban-breeze, urban heat island, surface energy balance, numerical simulations, Meso-NH, TEB, scaling, CAPITOUL

Thèse

Une Approche Observationnel, Numérique et Théorique à la circulation de Brise Urbaine diurne pour les villes continentales

Julia HIDALGO

Resumé:

D'un point de vue social, économique et météorologique, l'environnement urbain est un système complexe qui mérite l'attention d'une communauté scientifique multidisciplinaire. La ville modifie les conditions météorologiques locales et régionales. La ville modifie le bilan d'énergie de surface ainsi que la composition de l'atmosphère comparée aux terrains naturels présents aux alentours. L'îlot de chaleur urbain en est la plus évidente conséquence. L'impact sur la dynamique de vent est du à la fois à l'hétérogénéité des surfaces, à la rugosité plus importante et aux gradients horizontaux de température entre les environnements urbains et ruraux. Cet impact est plus difficile à observer mais il est importante pour la gestion de la qualité d'air, la conception de structures et le confort urbain.

Cette étude se focalise sur la circulation locale appelée circulation de brise urbaine qui est generée en présence d'un îlot de chaleur urbain diurne, avec un ciel sans nuages et des vents régionaux très faibles. Différentes approches sont combinées pour avancer dans la connaissance de ce phénomène de mésoéchelle: Une étude expérimentale de la brise urbaine, utilisant les données d'observation de la campagne de CAPITOUL effectuée à Toulouse entre février 2004 et mars 2005. Une approche numérique employant des simulations à haute résolution (250 m) effectuées avec le modèle atmosphérique non-hydrostatique Meso-NH, couplé avec un schéma de surface urbain TEB, a permis de quantifier les effets urbains 3D de mésoéchelle non mesurés. Ces deux approches ont permis d'obtenir l'intensité et l'étendue des branches convergentes et divergentes de la brise, les vitesses de convection verticales et de quantifier la perturbation sur les champs de température et d'humidité. Pour terminer, une étude théorique des profils thermodynamiques de température et de vent utilisant des simulations numériques 3D à haute résolution (500 m) est la stratégie retenue pour examiner la dépendance des processus physiques des forçages externes impliqués dans la circulation de brise urbaine diurne. Un ensemble de lois simples décrivant les caractéristiques de la brise en fonction des variables est présenté.

Mots-clés : Brise urbaine, îlot de chaleur urbain, Meso-NH, TEB, scaling, CAPITOUL