Meteorol Atmos Phys 102, 243–262 (2008)
DOI 10.1007/s00703-008-0345-0
Printed in The Netherlands

Meteorology and Atmospheric Physics

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Urban-breeze circulation during the CAPITOUL experiment: numerical simulations

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With 9 Figures

Received 14 May 2007; Accepted 26 October 2008
Published online 4 December 2008

Summary

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. 2004–2005). 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 50 m 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.

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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. 2004–2005; 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 $1–2\,\mathrm{m\,s^{-1}}$ 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 et al. 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 $+5\,^{\circ}\mathrm{C}$ UHI during the 3rd to 4th July 2004, a daytime gradient of surface sensible heat flux between the urban and rural zones of $200\,\mathrm{W\,m^{-2}}$ creating a daytime UHI with $+1\,^{\circ}\mathrm{C}$ 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 and Planton 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) (Fig. 1a–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 1800×1800 km, 300×300 km, 60×60 km and 30×30 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 IOP5 (3rd and 4th July 2004) of the CAPITOUL experiment. The whole period

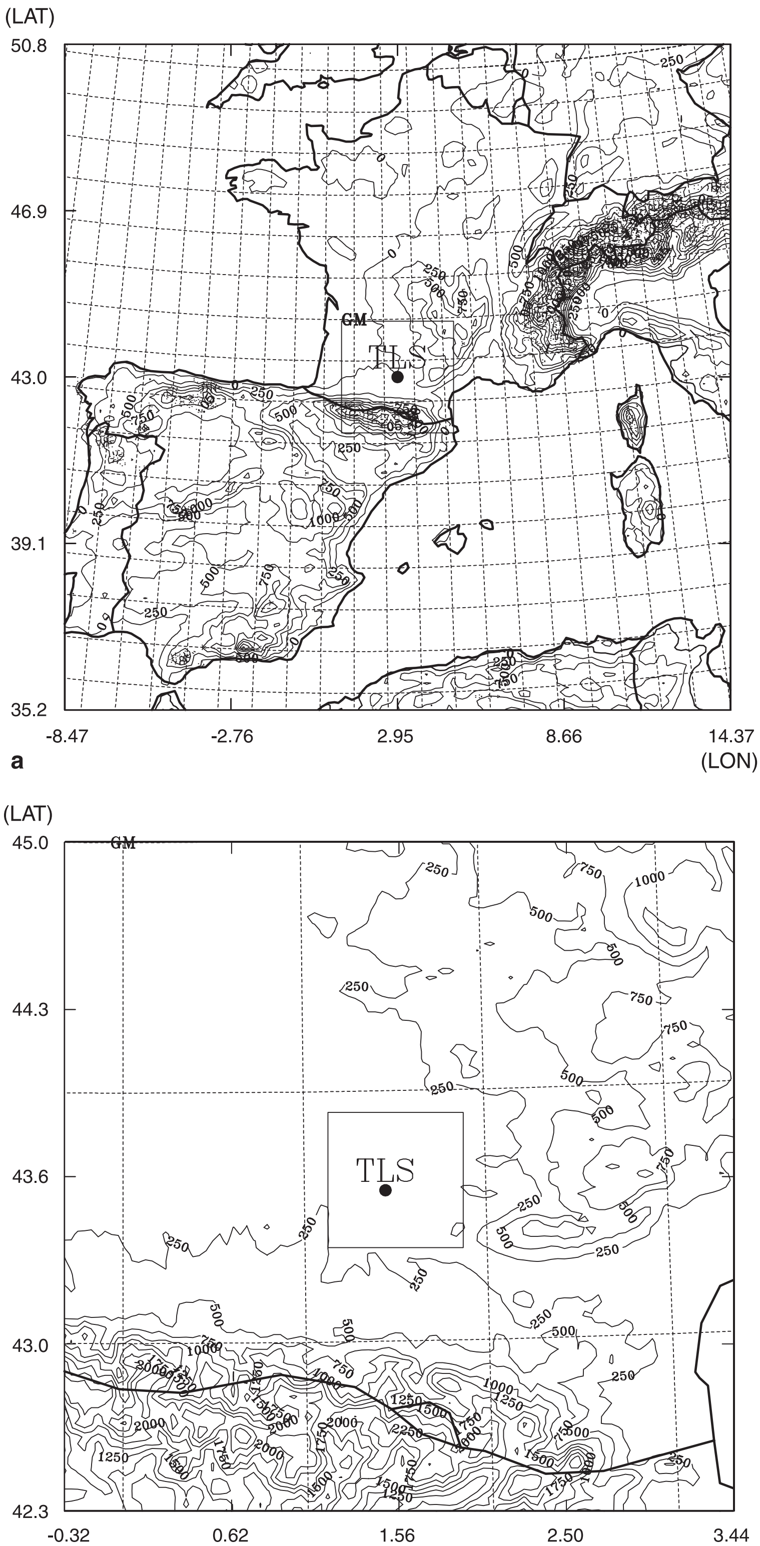


Fig. 1. Horizontal domain of models at (**a**) 12 km (M1), (**b**) 3 km (M2), (**c**) 1 km (M3) and 0.25 km (M4) (black square) resolution. The isolines represent the orography in meters (above sea level in M1 and M2, above city centre level in M3). The fraction of urban cover is presented in a scale of greys in the M4 domain

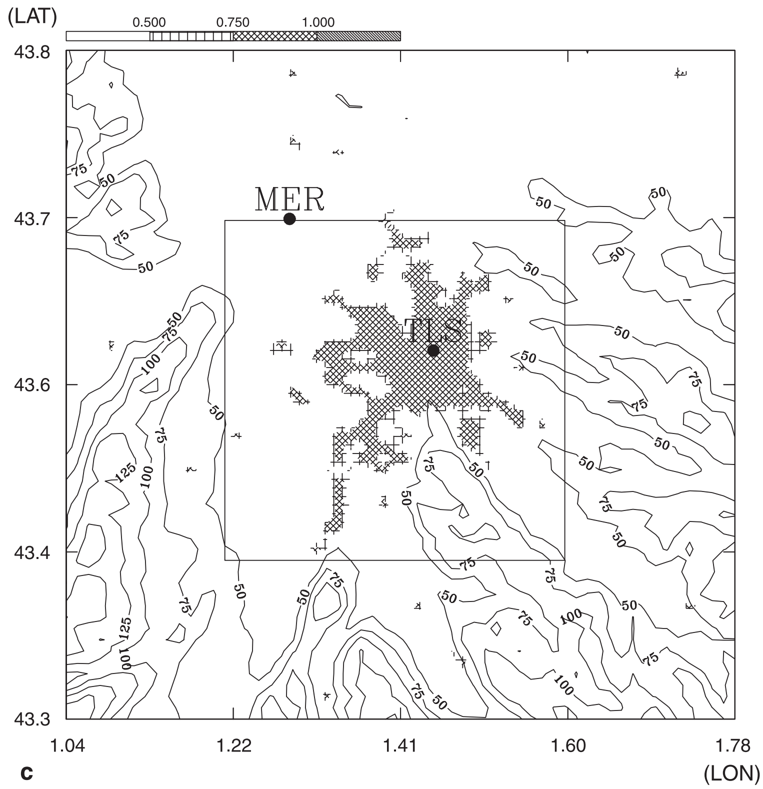


Fig. 1 (*continued*)

(48 h) 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 and Lacarrère (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 Ecoclimap 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 mixing 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 ($\sim$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 Fig. 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. 2008; their Fig. 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. 2008; their fig. 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. 2008; their fig. 8b).

Figure 2 shows the horizontal wind modelled by URB(M3) (1 km of horizontal resolution, 60×60 km of spatial coverage). Outputs are averaged for the same period of the flight (12.30–15.30 UTC) in order to capture the mean horizontal wind field in the region. It appears that at low levels (Fig. 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 (Fig. 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 Fig. 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 (Fig. 3).

For the flight leg P3 (at 1650 m of height) 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 $g\,kg^{-1}$. 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

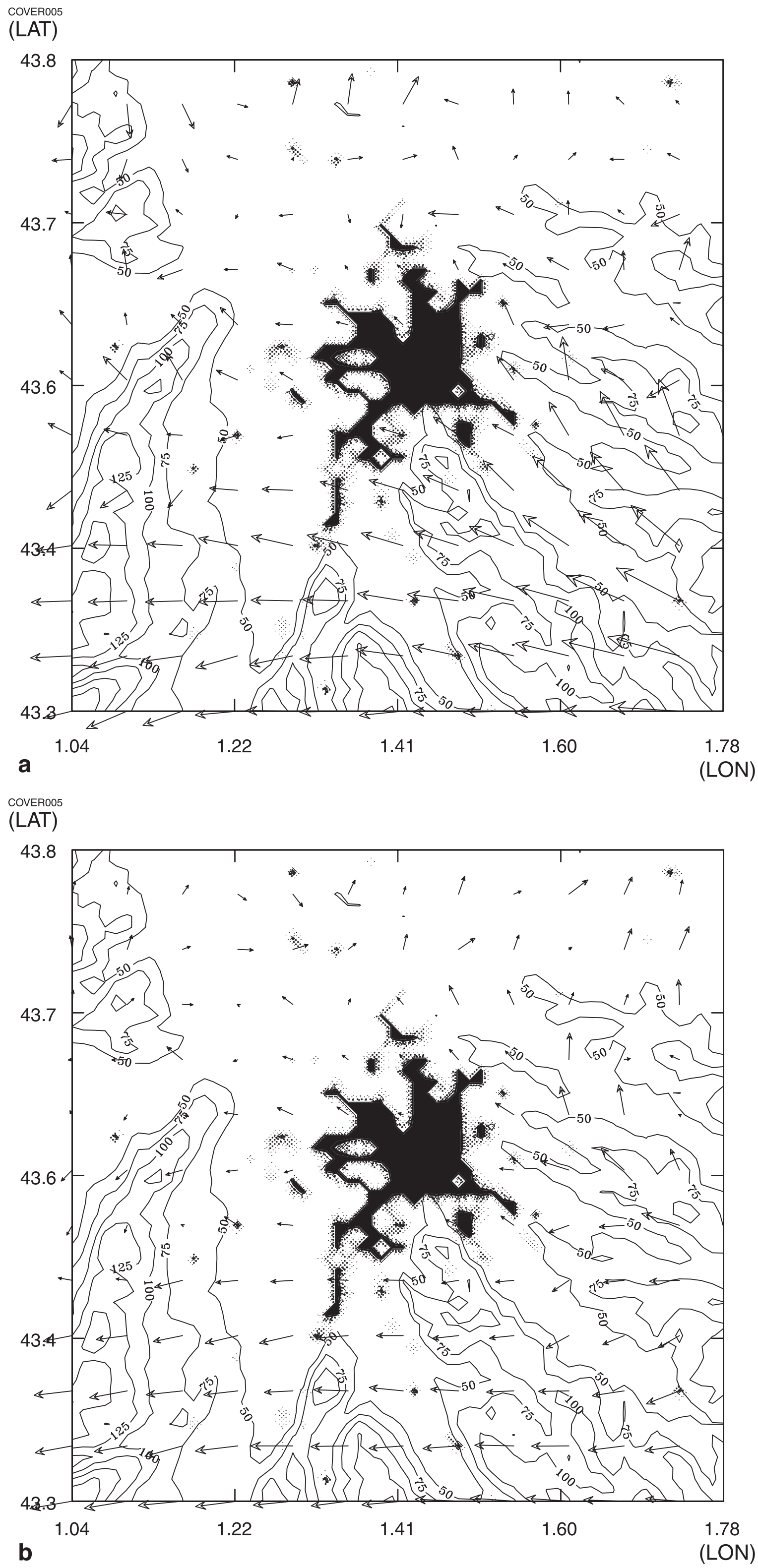
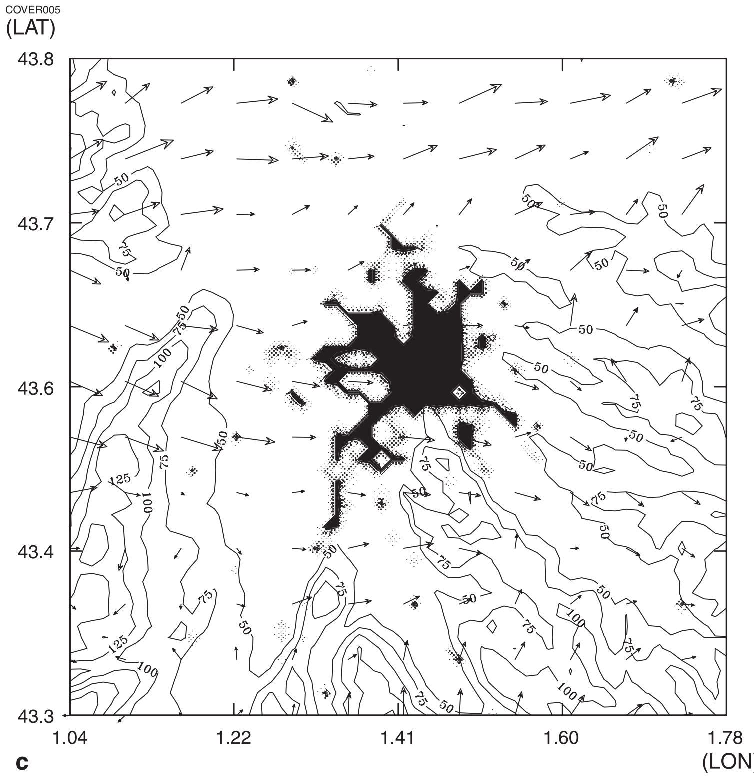


Fig. 2. Horizontal wind field velocity and module modelled by M3 over plotted to the relief in meters above city level. The urbanized area is presented in the black area. Average over 3 h (12.30–15.30 UTC). Horizontal cross-sections at 350 m (**a**), 1100 m (**b**) and 1650 m (**c**) of height, respectively



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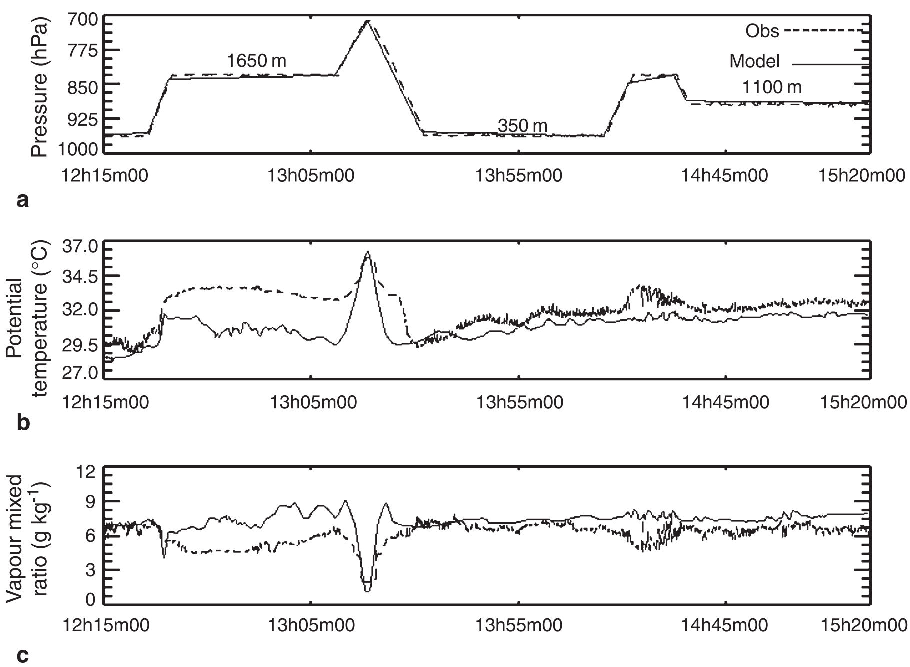


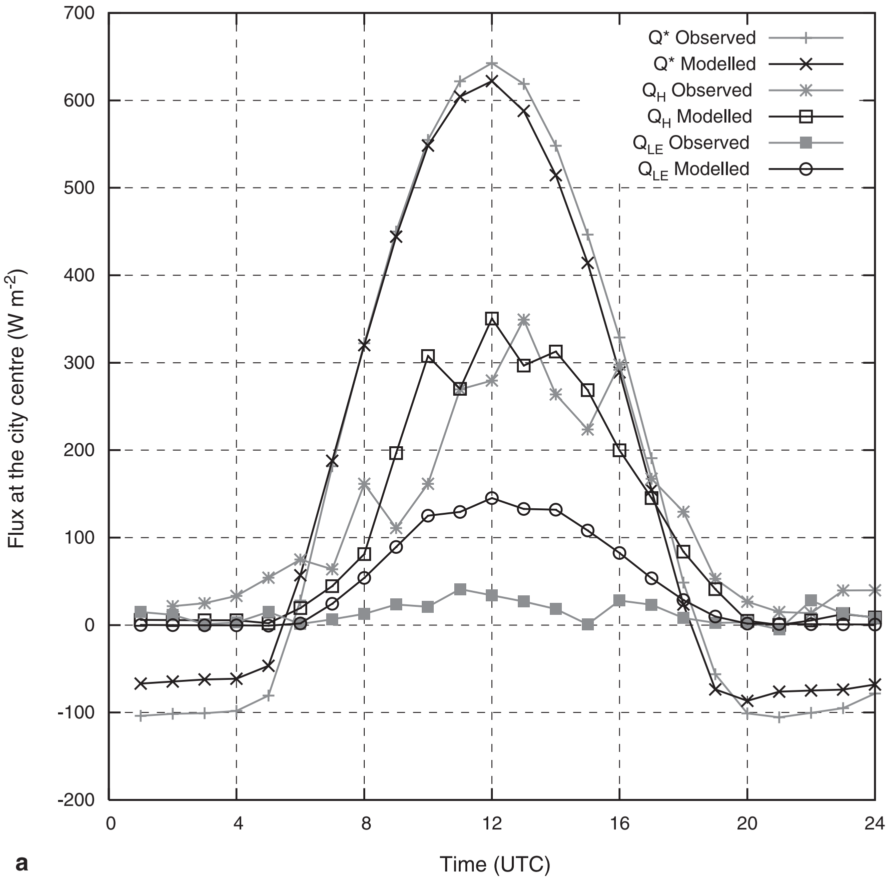
Fig. 3. Time series of pressure (**a**), potential temperature (**b**) and vapour mixing ratio (**c**) observed by the Piper Aztec aircraft the 4th July and modelled by MesoNH (URB(M4) and URB(M3) when the aircraft goes out of the M4 domain)

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 surround-



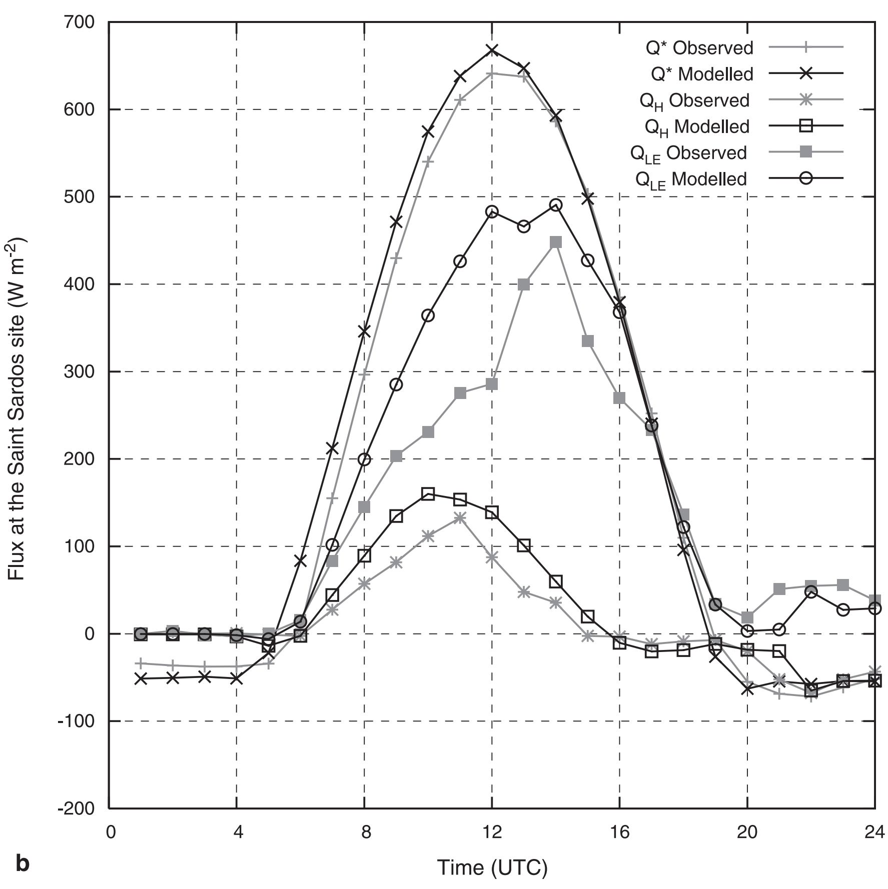


Fig. 4. Energy balance components modelled (solid line) and observed (dotted line) by URB(M4), for the 4th July 2004 in the central tower (**a**) and in the rural sites (Saint Sardos (**b**) and Fauga (**c**)). Flux densities of net all-wave radiation (Q^*), sensible heat (Q_H), latent heat (Q_{LE})

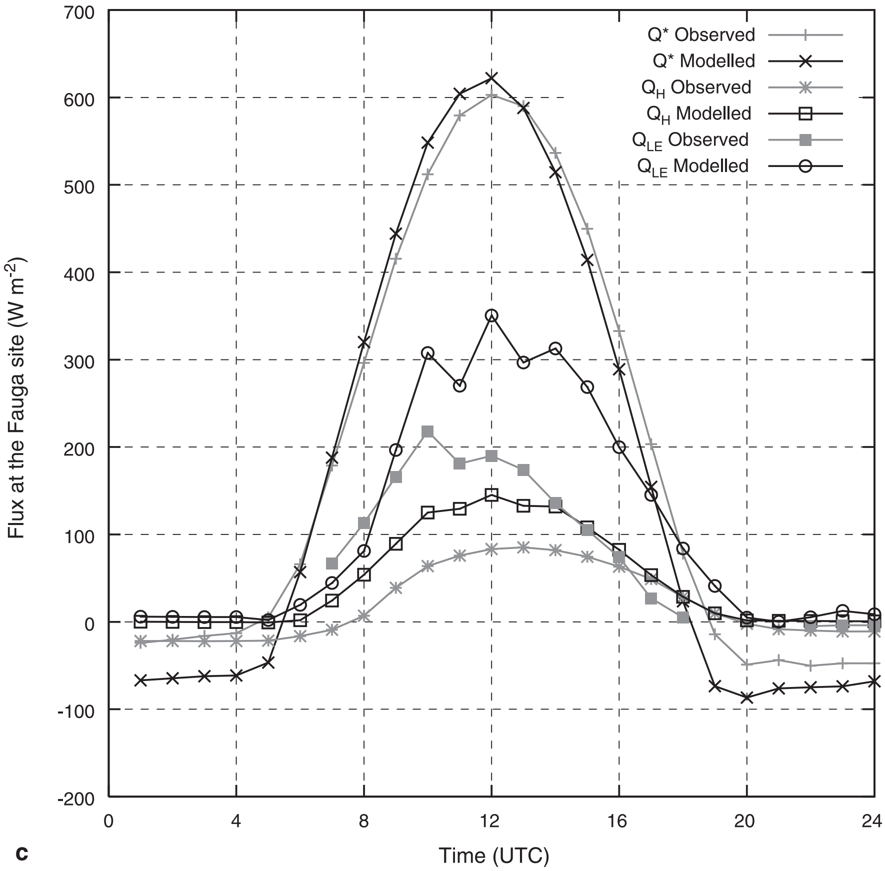


Fig. 4 (*continued*)

ings. 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 by 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. (2008).

The shape of the daily cycle of net all-wave radiation Q^* is simulated by the model for both environments (Fig. 4). In the city centre, there are small biases in the simulation of the negative nocturnal values ($-100\,\mathrm{W\,m^{-2}}$ observed at 00.00–04.00 UTC and at 20.00–24.00 UTC, $-70\,\mathrm{W\,m^{-2}}$ 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 $\mathrm{W\,m^{-2}}$ and in the rural site 50–200 $\mathrm{W\,m^{-2}}$ 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 (12.00–18.00 UTC), the sensible heat in the rural sites have small values (0–100 $\mathrm{W\,m^{-2}}$) whereas the city centre have, during the same period, strong Q_H positive values (350 $\mathrm{W\,m^{-2}}$). 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.

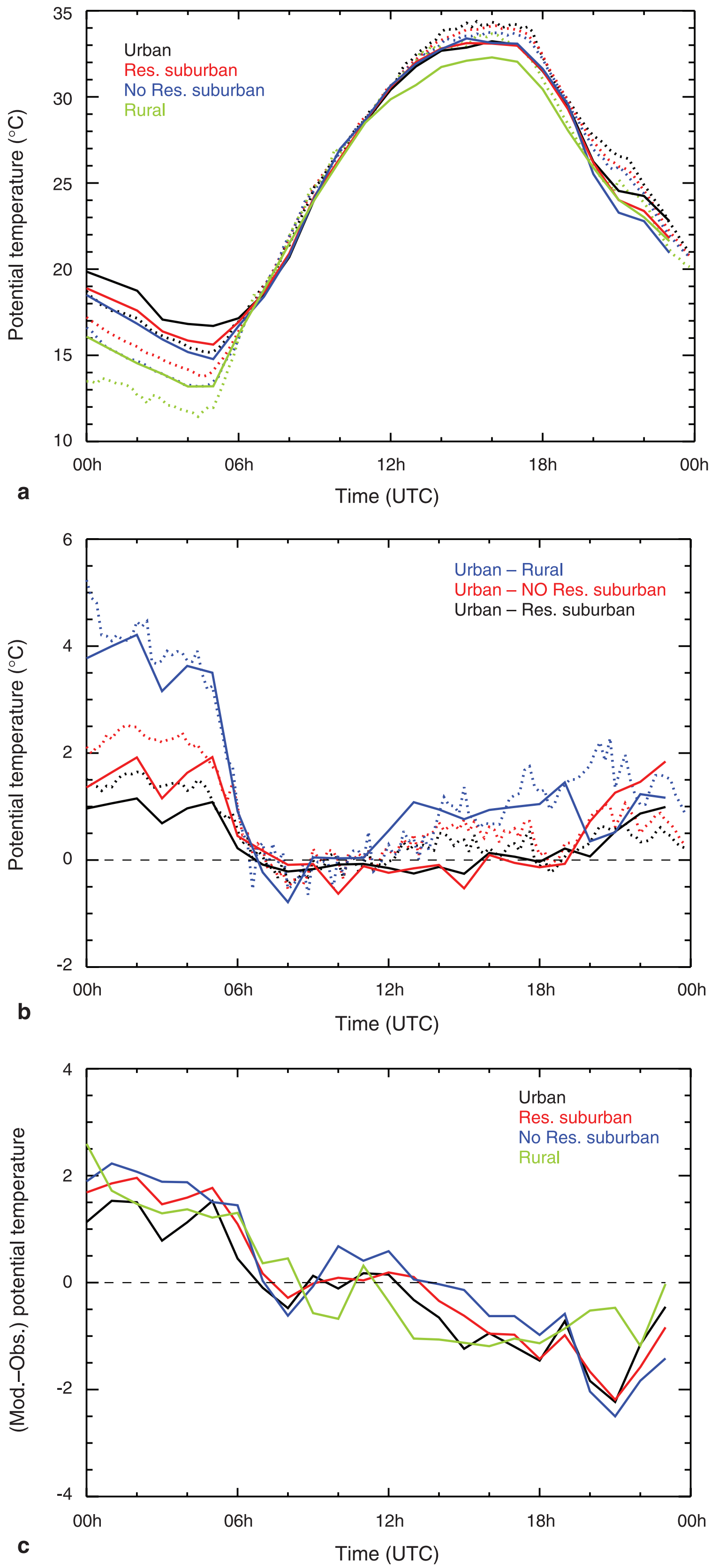


Fig. 5. Temporal evolution of observed (dotted line) and modelled (solid line) 2 m potential temperature (**a**), urban heat island intensity (**b**) and bias (**c**), the 4th July. Output values from the simulation URB (M4) at 2 m have been extracted at grid points corresponding to the location of the surface stations and averaged by urbanization class

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 3rd to 4th 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 (Fig. 5b). In the rural zone, the model overestimates the temperature by 2.5 °C at 00.00 UTC (Fig. 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 decreases 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 (Fig. 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 (Fig. 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 (Fig. 5b).

For the period of the breeze (12.00–18.00 UTC), the bias remains lower than 1.5 °C (Fig. 5c) being the residential and non-residential suburban zones the best areas simulated. The daytime heat island observed during this period (1–1.5 °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 (Fig. 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 (Fig. 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 (Fig. 6a).

MesoNH simulates the observed humidity from 00.00 to 12.00 UTC with a bias lower than 0.5 g kg^{-1} (Fig. 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

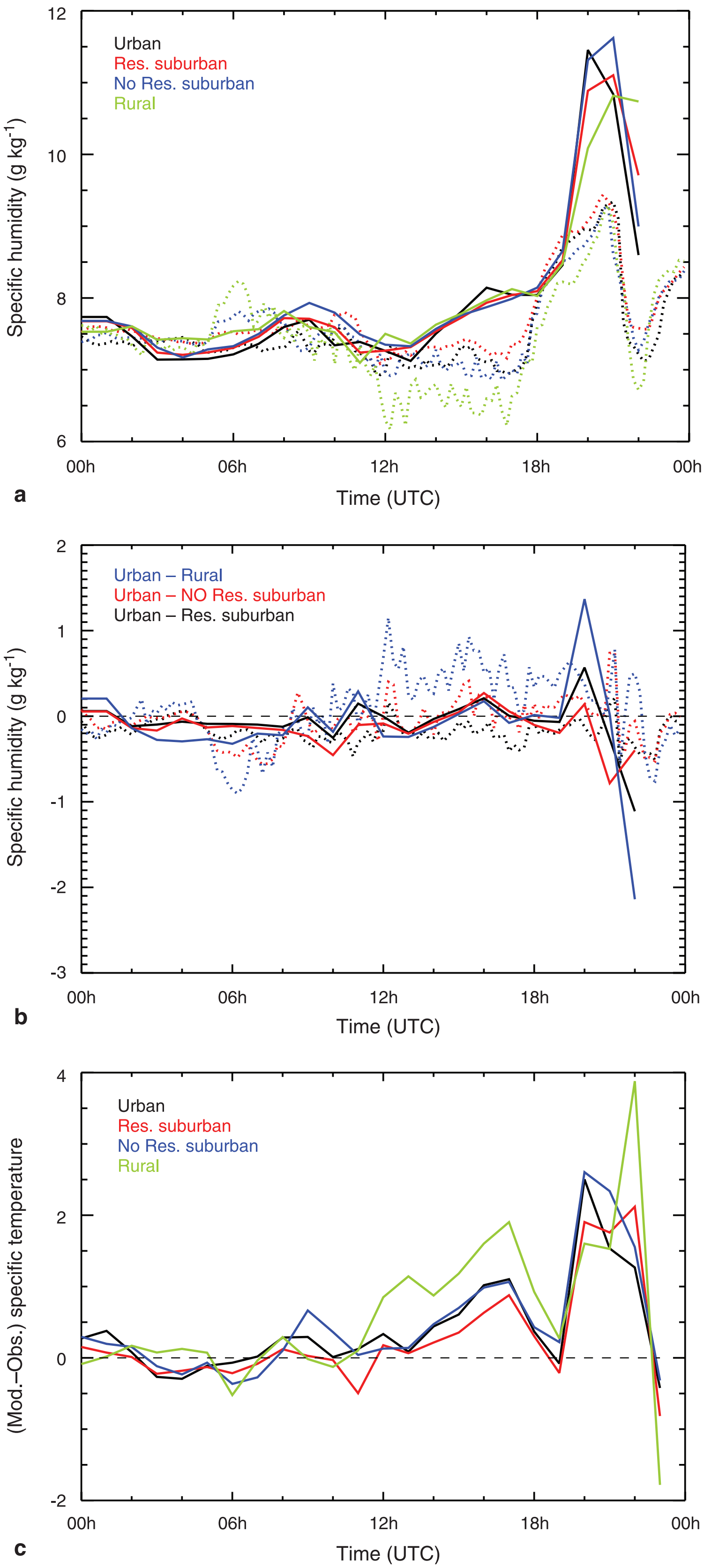


Fig. 6. Temporal evolution of observed and modelled 2 m air specific humidity (**a**), humidity island (**b**), and bias (**c**), the 4th July. Output values from the simulation URB and the model M4 at 2 m have been extracted at grid points corresponding to the location of the surface stations and averaged by urbanization class

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. However humidity is of less importance concerning the urban breeze system compared to temperature.

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 Sect. 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) where the urbanized areas have been removed.

The UHI between urban and rural zones is minimal for the period 09.30–11.30 UTC (Fig. 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 (12.30–15.30 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. 2008; their Fig. 7a–c).

Figure 7a shows a 30 km vertical cross-section in the direction of the mean wind (NW–SE, Fig. 7b). 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 where 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.

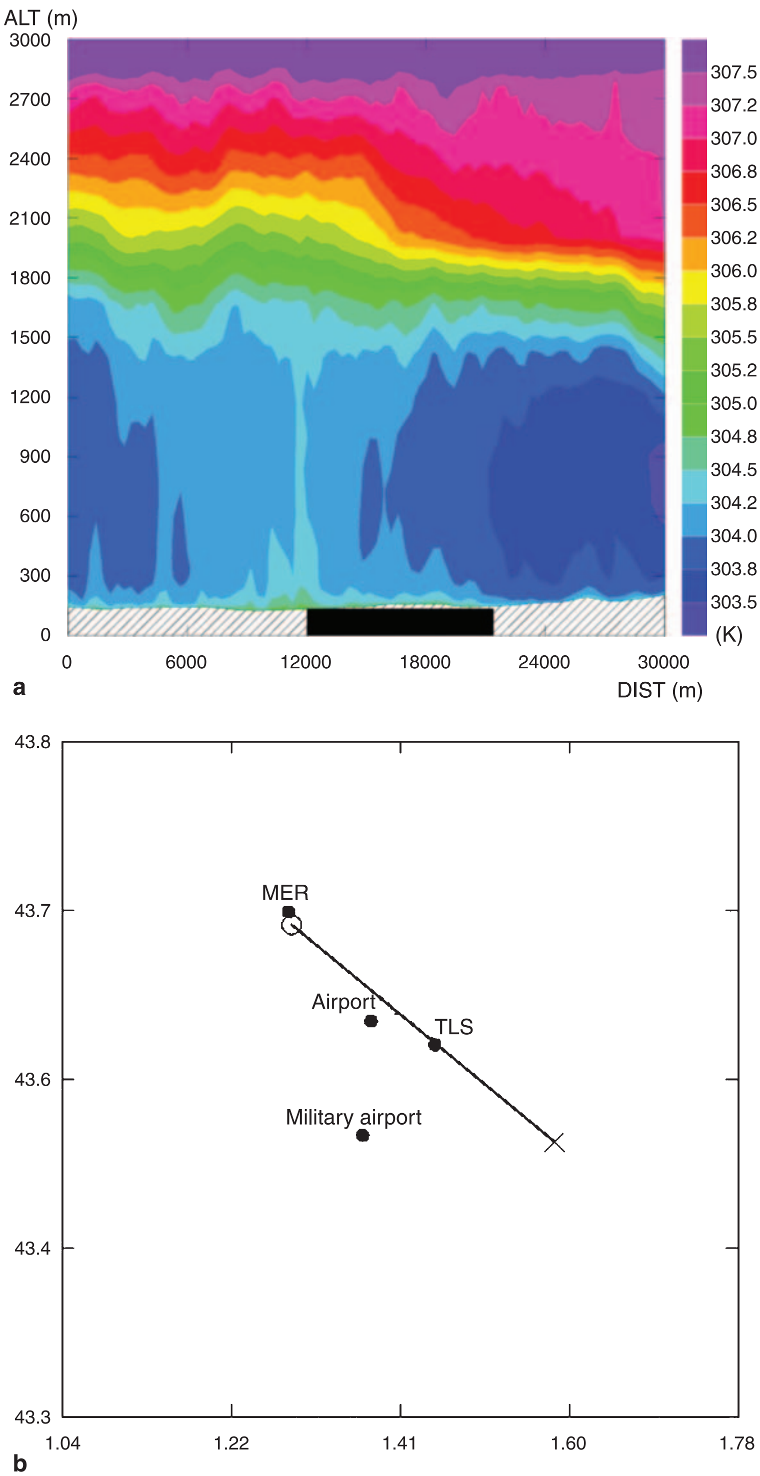


Fig. 7. Vertical NW–SE cross-section of mean potential temperature (13.30–14.30 UTC). The black strip indicates the horizontal extension of Toulouse area. Horizontal projection of the vertical cross-section (**b**)

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 ($URB_{12h30-15h30}$–$RUR_{12h30-15h30}$) is shown as a vertical cross-section in the direction of the mean wind (NW–SE) in Fig. 8a. The section of 30 km long, crosses Toulouse in city centre and ends near Merville city (ER) in order to cover the two sites (urban

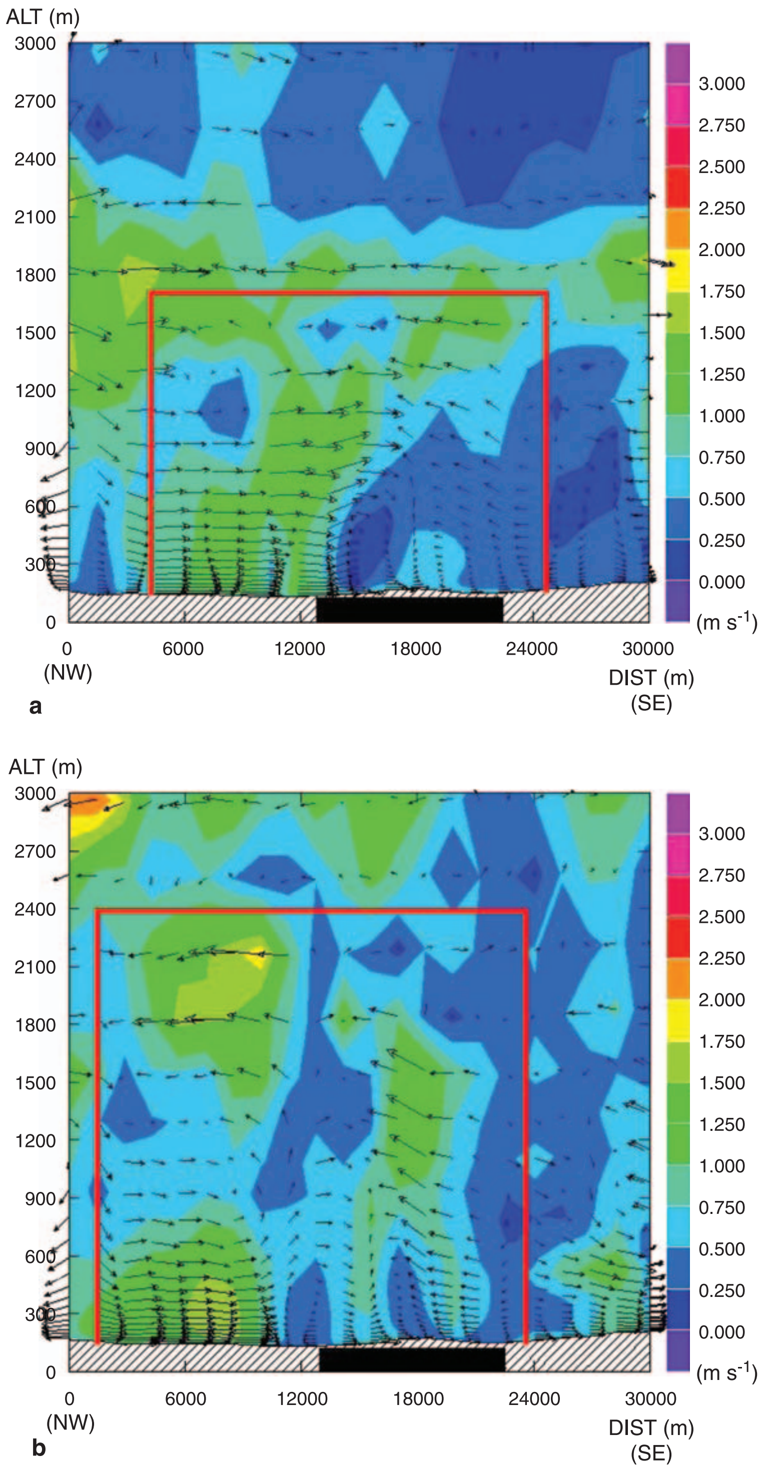


Fig. 8. Vertical NW-SE cross-section of the anomaly wind (URB(M3)-RUR(M3)) from 12.30 to 15.30 UTC (**a**) and from 15.00 to 18.00 UTC (**b**) over plotted to the horizontal wind intensity. The black strip indicates the horizontal extension of Toulouse area. The red square indicates the estimated horizontal and vertical extension of the breeze. The horizontal projection of the vertical cross-section is in Fig. 7b

and rural) from where the radiosondes were launched during the IOP5 (Fig. 7b).

The TEB scheme in the simulation URB allows to take into account the two processes cited in Sect. 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 Figs. 5b and 7a. 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 (Fig. 8a).

5.4 Time-evolution of the breeze

During the CAPITOUL campaign a north-westerly flow at the surface and a south-easterly flow at upper-levels was identified in the radio soundings of 18.00 UTC. 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 Sect. 5.3 were applied for the period 15.00–18.00 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 Sect. 5.3 is shown in Fig. 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 (12.00–18.00 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 1–1.5 °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),

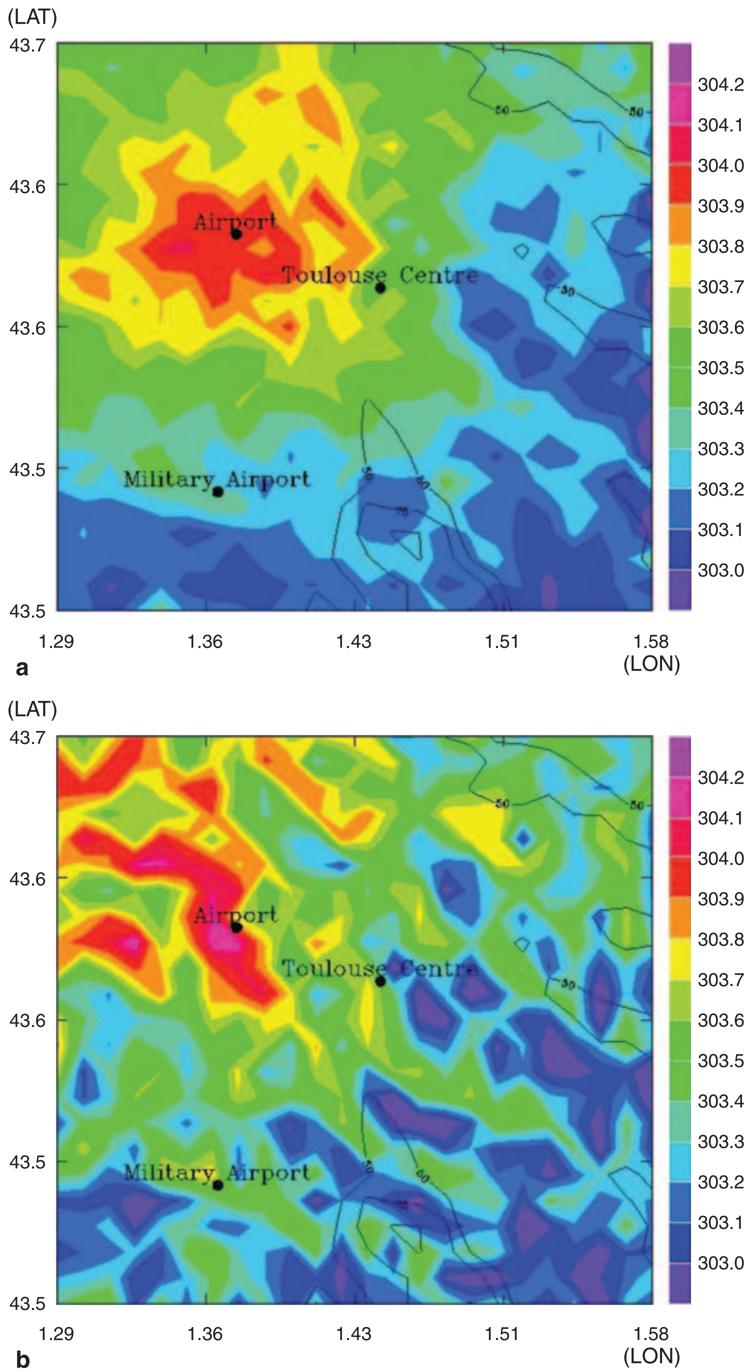


Fig. 9. Horizontal cross-section of the modelled potential temperature at 14.00 UTC (**a**) by URB(M3) and (**b**) URB(M3)-1 km at 350 m of height, (**c**) by URB(M3) and (**d**) URB(M3)-1 km at 1100 m of altitude. Isolines represent the orography (in meters above city centre)

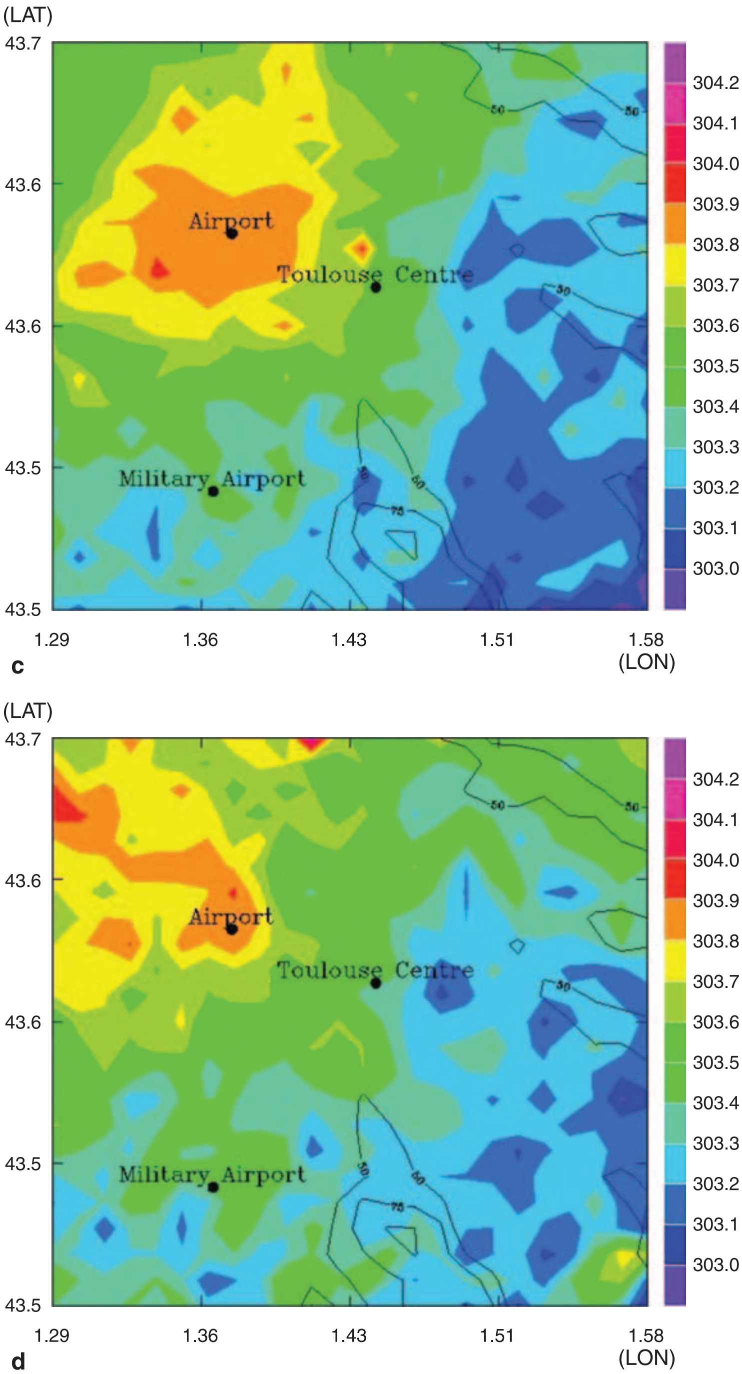


Fig. 9 *(continued)*

1 km (M3) and 0.25 km (M4) (Fig. 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 and Lacarrère (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 1 km only. An extra run, URB(M3)-1 km, 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 (Fig. 9a, b) and 1100 m (Fig. 9c, d) of height are presented for simulations URB(M3) and URB(M3)-1 km 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, Fig. 9a, c) 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)-1 km (so without a M4 nested model, Fig. 9b, d) 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)-1 km 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. URB(M3) 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.

Acknowlegement

This research was performed with a PhD grant co-founded by the French National Centre of Meteorological Research and the FAO9 team of the University of Vigo in Spain (Education and Science Ministry; DIMPRE project, Ref: GL 2004-05187-C03-02/CLI). The authors would like to thank the kindly help of Sue Grimmond and two anonymous reviewers who offered a critical review of this paper.

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