SIMULATION OF A SUMMER URBAN BREEZE OVER PARIS

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Abstract. Numerical simulations for an anticyclonic summer episode in the Paris area have been performed at the meso-γ scale for a 48-hour period, and compared to observations from a dense operational observational network. The meteorological stations have been classified, according to the extent of urbanization of their surroundings, into four classes (central Paris, urban, suburban, and rural). The atmospheric model, coupled with an urban surface scheme, correctly reproduces the temperature (within 1 K from the observations) and humidity. The intense urban heat island during the night is also well represented.

Following the validation, the model is used to quantify atmospheric effects of Paris on the boundary layer, through a comparison with a purely rural simulation. At night, the model simulates a neutral or even slightly unstable boundary layer to a depth of 200 m over the city. In contrast, a very stable layer formed in the countryside. During the day, the boundary layer was more turbulent and 500 m deeper over Paris; vertical velocities of up to 1 m s^{-1} were created over the city. This leads to an urban breeze with convergence at low levels (with winds around 5 to 7 m s^{-1}), and divergence at the boundary-layer top (with similar wind speeds). The horizontal extent of the breeze reaches for more than 50 km from the city centre, and could have an important impact on pollutant diffusion in the area for calm days.

Finally, three other spring cases are presented briefly. These show that an urban breeze develops if the synoptic wind is weak enough or disorganized; an urban plume develops otherwise.

Keywords: Atmospheric model, Numerical simulation, Urban breeze, Urban heat island, Urban plume.

1. Introduction

From an energetic point of view, the urban surface behaves very differently to vegetation cover or even bare soil surfaces. Many experimental campaigns undertaken in large cities have shown such results; see for example the results from St. Louis (Seaman et al., 1988), Chicago, Los Angeles, Sacramento and Tucson (Grimmond and Oke, 1995), Tokyo (Yoshikado, 1992), Zurich (Rotach, 1995), Athens (Svensson, 1995, 1998), Paris (Menut, 1997; Menut et al., 1999; Troude, 1999; Troude et al., 2001), Mexico City (Oke et al., 1999) and Milan (Argentini et al., 1999).

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One of the consequences of contrasting surface energy fluxes between cities and their surroundings is the development of an urban heat island (UHI) (i.e., warmer air over the city, especially at night) in anticyclonic conditions (see the extensive review by Oke, 1987). The nighttime maximum of the UHI is due to the release of the heat stored in the buildings during the day (or produced by domestic heating) in the buildings. This heat release is large enough to produce a small positive turbulent heat flux to the atmosphere. As a result, the urban boundary layer (UBL) does not become stable at night, as observed by Nakamura and Oke (1988), Uno et al. (1988), and Rotach (1995), among others.

The aim of our study is to quantify the effects of a major urban agglomeration, in this case Paris, on the atmospheric boundary layer. Some effects, such as the UHI intensity, are easily detectable by a meteorological surface network (provided that at least one heavily urbanized station and a few rural stations are present). However, other effects, such as the enhancement of convection, are less straightforward to document using a surface network. Some effects are difficult to measure, for example the urban area-averaged vertical wind velocity in an urban breeze. Although, these can be measured by aircraft, authorizations to fly above a city are not easy to obtain.

Here, a numerical simulation strategy is used. An urban breeze event is simulated with an atmospheric numerical model (Meso-NH) above the area of interest, and validated against observations. The validated simulated fields in turn were used to quantify the unmeasured mesoscale urban effects.

The area around Paris in France has been chosen for three reasons. First, it is a major agglomeration of approximately ten million inhabitants. Second, a relatively dense network of meteorological stations is in existence (see Figure 1), and which can be used to validate the model. Third, the geographic setting is quite simple: Paris is situated far from the sea, in a valley surrounded by plateaus, where the orography is beneath 200 m (see Figure 2). In this paper, the summer anticyclonic situation of the 12 July 1994 is studied in detail; this was a day where strong pollution was encountered. Only the thermal and dynamic aspects of the boundary layer will be investigated here. In the last section, three other spring anticyclonic cases will be considered briefly.

2. Presentation of the Numerical Simulation

In this study, the TEB (Town Energy Balance) urban scheme and the Meso-NH atmospheric model are coupled. TEB has been recently developed (Masson, 2000) to parameterize town-atmosphere dynamic and thermodynamic interactions. It is based on the well-known ‘urban canyon’ geometric model (Oke, 1987), applied in TEB to an entire urban area. The city is described as a group of identical streets running in all directions. Three surface types are defined (roads, streets and walls). The TEB scheme computes the surface energy budget for every surface.

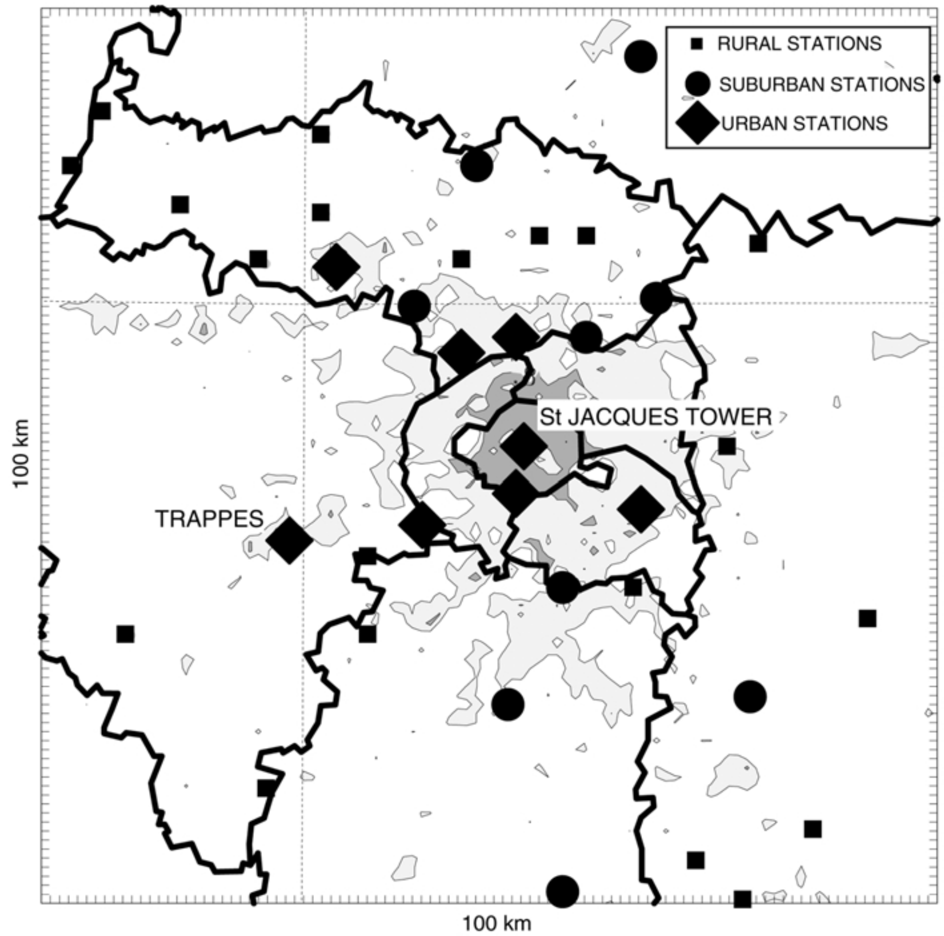

Figure 1. Meteo-France observational network in the Paris area. The extent of urbanization defined by the model is represented: Light grey = 50% < urbanization < 80% and dark grey = urbanization > 80%.

The canyon is defined by three geometric parameters (width and height of the buildings, and width of the streets) that are constant in a grid box of the model. The TEB scheme considers anthropogenic heat fluxes in addition to specifying sensible and latent fluxes for traffic and industry. An internal air temperature within the buildings (around 17 °C) is imposed to take into account the domestic heating. The TEB scheme computes radiation trapping inside the canyon (longwave and solar radiation), a process that depends on the sky-view factor of the canyon computed according to Noilhan (1981) and the zenith angle. The momentum fluxes are parameterized using the Monin–Obukhov similarity theory for the entire urban area. For the heat fluxes, two different urban sources are considered: the roofs and the

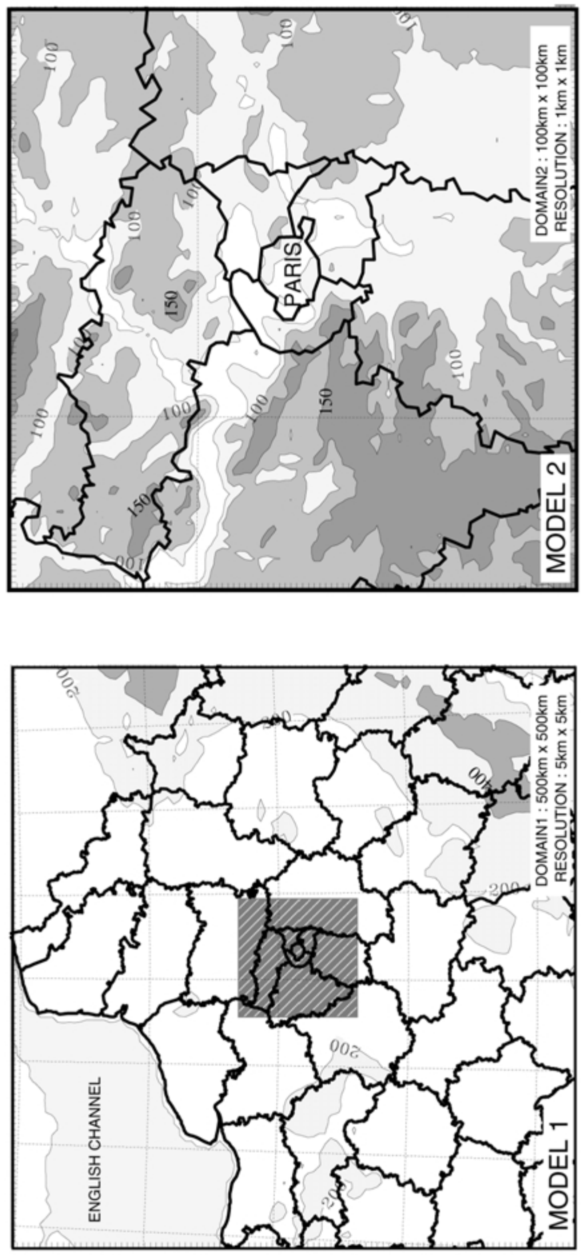

Figure 2. The two nested models used for the simulation. Elevation is displayed every 200 m for model 1 and every 50 m for model 2.

canyons. These contributions are computed separately and averaged according to the respective horizontal areas of roofs and canyons.

For natural covers, surface exchanges are computed with the ISBA scheme (Noilhan and Planton, 1989). The CORINE land cover classification (CEC, 1993) is used to provide an accurate description of the surface, and contains 44 cover classes, 11 of which are urbanized. The resolution of the dataset is 250 m, such a high resolution allowing for the discrimination of the degree of urbanization of the surface, from continuous urban fabric (in the city of Paris itself), to purely rural areas (mainly crops or forest in the region surrounding Paris). The three most representative urbanized covers are continuous urban fabric, discontinuous urban fabric (the suburban area), and the industrial and commercial zones. The parameters necessary to run both surface schemes (TEB and ISBA) are derived from the cover types. The parameters are computed on 1 km by 1 km grid squares to match the Meso-NH grid. If several cover types are present in one square, the parameters are averaged according to the relative areas of the cover types. A 10 percent coverage of gardens or parks is assumed for central Paris, based on estimates from aerial photographs. The map of the resulting extent of urbanization is shown in Figure 1.

The simulation was performed with the Meso-NH atmospheric model (Lafore et al., 1998). Two nested models are used; the first domain (model 1) covers a 500 km $\times$ 500 km area (100 $\times$ 100 points) with a 5-km resolution. The second domain (model 2) has the same number of points but with a 1-km horizontal resolution, and hence covers a 100 km $\times$ 100 km area (see Figure 2). The boundary and initial conditions of the larger domain are defined by the ECMWF (European Centre for Medium-range Weather Forecasts) analyses updated every six hours. The two models use two-way grid-nesting interactions. At first, the initial conditions of model 2 are given by model 1; then, at every time step, model 1 defines the boundary conditions of model 2 and the outputs of model 2 are averaged into model 1. For both models to adequately resolve the boundary-layer processes, the vertical grid includes 37 levels, with 28 in the first three kilometres. The first level is situated 2.5 m above the roofs.

Simulation runs were performed over a 48-h time period, from the 11 July, 1200 UTC, to the 13 July 1994, 1200 UTC (with outputs every three hours).

The different parametrizations used are: the turbulence scheme with the Bougeault-Lacarrère mixing length (Bougeault and Lacarrère, 1989), a warm microphysical scheme, the ECMWF radiative scheme, a soil and vegetation scheme (ISBA, Interactions between the Soil, Biosphere, and Atmosphere), and the TEB scheme.

3. Validation of the Simulation

3.1. Observational network

A comparison has been performed between surface observations and model outputs in order to validate the simulation. The surface network in the area of interest (second domain) contains 37 operational meteorological stations. All stations have the measured temperature at a height of 2 m, and some have also measured humidity at 2 m and wind at 10 m. The stations has been separated into four categories (see Figure 1):

- The St-Jacques Tower station –
  this station is located in the centre of Paris, a few hundred metres from the Seine River and Notre-Dame. This is an old stone tower.
- 8 urban stations –
  located in areas where the extent of urbanization is over 50 percent.
- 9 suburban stations –
  located in areas where the extent of urbanization is between 10 and 50 percent.
- 20 rural stations –
  located in areas where the extent of urbanization is under 10 percent.

3.2. Comparison of the surface parameters

Output values of parameters have been extracted at grid points corresponding to the location of the stations. Then, both observations and simulation output are averaged according to the four classes defined in the previous section. For each categories, comparisons were plotted for the wind at 10 m and the temperature and the mixing ratio at 2 m.

The wind measured at the rural stations (see Figure 3c) situated far from Paris, provides information on the regional conditions in the domain. During the period of interest, the flow stayed weak in the boundary layer (between 1 and 3 m s^{-1}), and it was very variable both in space and time (not shown). For all the classes, the wind speed is stronger during the day than at the night (see Figures 3a–c), and reaches its maximum magnitude at the end of the morning in rural and suburban areas, but a little later at the urban stations. The wind is stronger in the middle of the day for urban and suburban stations, even though such stations are in areas of much larger roughness than the countryside. This unusual behaviour (see Figure 3d) may be related to the establishment of an urban breeze during the afternoon as discussed in Section 4.4.

Meso-NH does not succeed in representing the rapid increase in wind speed around 0800 UTC in rural and suburban areas; this effect is later and weaker in the simulation. In the city, however, this effect is simulated. The general synoptic conditions are changing on 13 July. The wind becomes stronger and presents a much more marked orientation from the north-west. The model does not show this

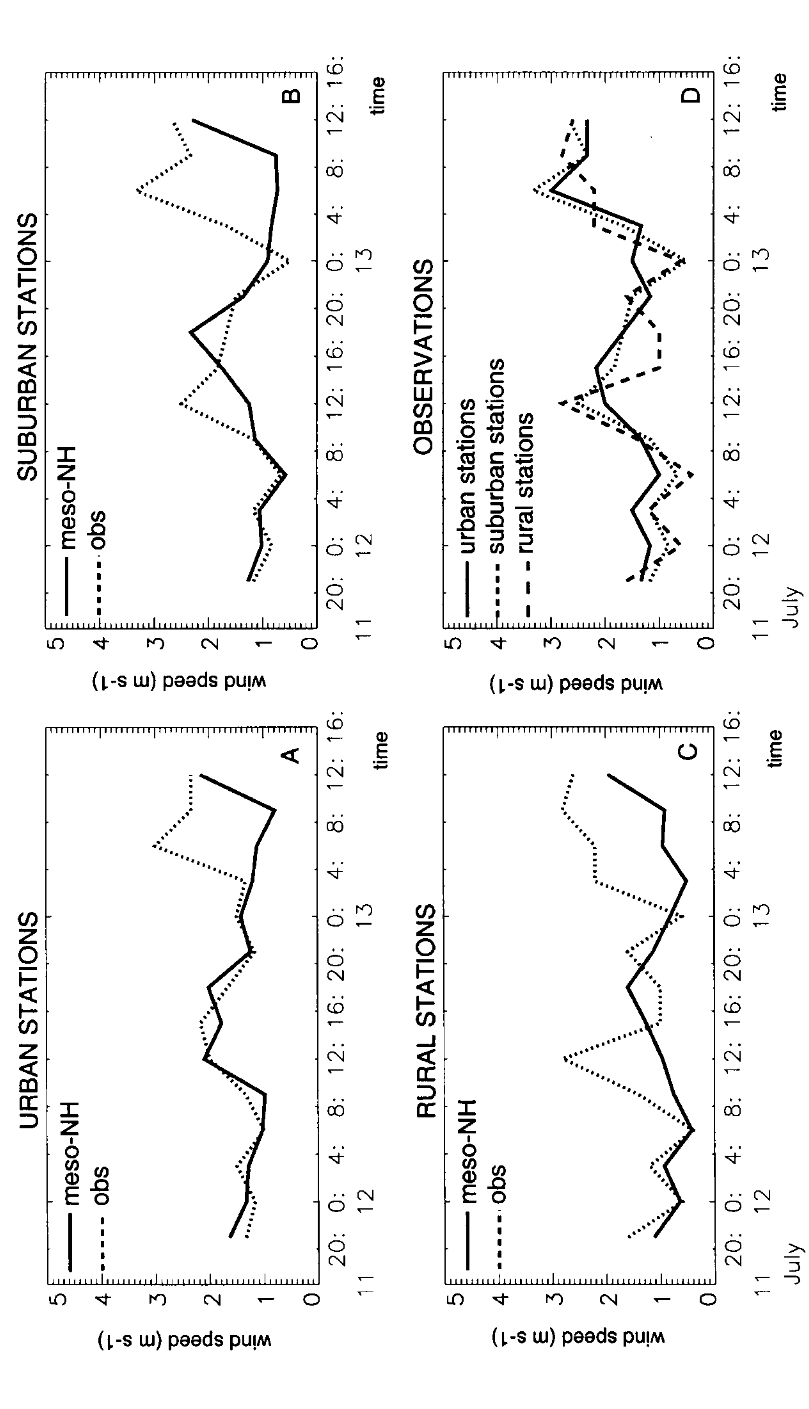

Figure 3. Comparison between the observed and simulated wind speeds at 10 m, averaged by urbanization class ((A), (B) and (C)). (D) Represents only the observed wind for urban, suburban and rural areas.

until nine hours later, the delay being induced by the lateral boundary conditions. The ECMWF analyses show an increase of the wind only around 0900 UTC.

Good correlations are found between model temperatures and observations for all the classes of urbanization (see Figure 4). The Meso-NH model seems to overestimate a little the temperature in urban and suburban areas. However, since most of these stations are situated in parks, observations of temperature and humidity are influenced by these vegetated areas. Therefore, observations are expected to be slightly lower than the actual urban temperature. For all the comparisons, the numerical model induces a cooling that is too linear, when compared with observations, which are more variable, greater in the evening (between 1800 and 2100 UTC) and weaker between 2100 and 0300 UTC. The daily warming process is better simulated by Meso-NH. At the end of the simulation, a stronger overestimation is found because the observed air temperature increases less on July 13. The wind increases after 0000 UTC 13 July 1994 (see Figure 3), inducing an important northwest cloud advection in the domain, thus limiting the warming up process. The nighttime conditions in the model are representative of clear-sky outputs because the ECMWF analyses delay the cloud cover entrance.

Typical behaviour for the different urban classes, concerning the cooling and warming up rates and magnitudes, can be defined. In urban areas (especially at the St Jacques tower station), the warming up begins later and is less important than in suburban and rural areas. The incident energy is used by the surfaces to heat the atmosphere, for heat storage, and as an evaporation flux. Since the heat storage in artificial materials is dominant in the morning in urban areas, the atmospheric warming is delayed and limited (see the description of the surface energy budget in Section 4.2). In the same way, urban cooling is reduced because of the heat release by the surfaces to the atmosphere.

One of the most pronounced effects of Paris on climate is the formation of an UHI, which results in a horizontal air temperature gradient between the city centre and the surroundings. This effect has been documented in previous studies for the Paris area (pollution episodes during ECLAP, Dupont et al., 1999). To illustrate this effect, the temperature difference between the St Jacques Tower station and the rural stations is plotted (see Figure 5). This gradient stays positive night and day. The rapid cooling in the countryside, combined with a nocturnal release of heat in the urban area, enhances the effect during the night. At 0300 UTC, the temperature difference reaches 8 °C between Paris and the countryside. Such a well developed heat island is not surprising for such a city and climatic conditions (anticyclonic situation and low wind). The UHI is less intense during the day; the temperature in the countryside increases more rapidly than in the city during the morning, and so the UHI decreases and is only 2 °C at 0900 UTC. After 1200 UTC, the cooling process begins with the decrease of solar radiation, inducing a slight increase of the UHI.

The results are also satisfying for moisture. The model succeeds in representing the observed variations of humidity (see Figure 6). Between 0800 and 2100 UTC,

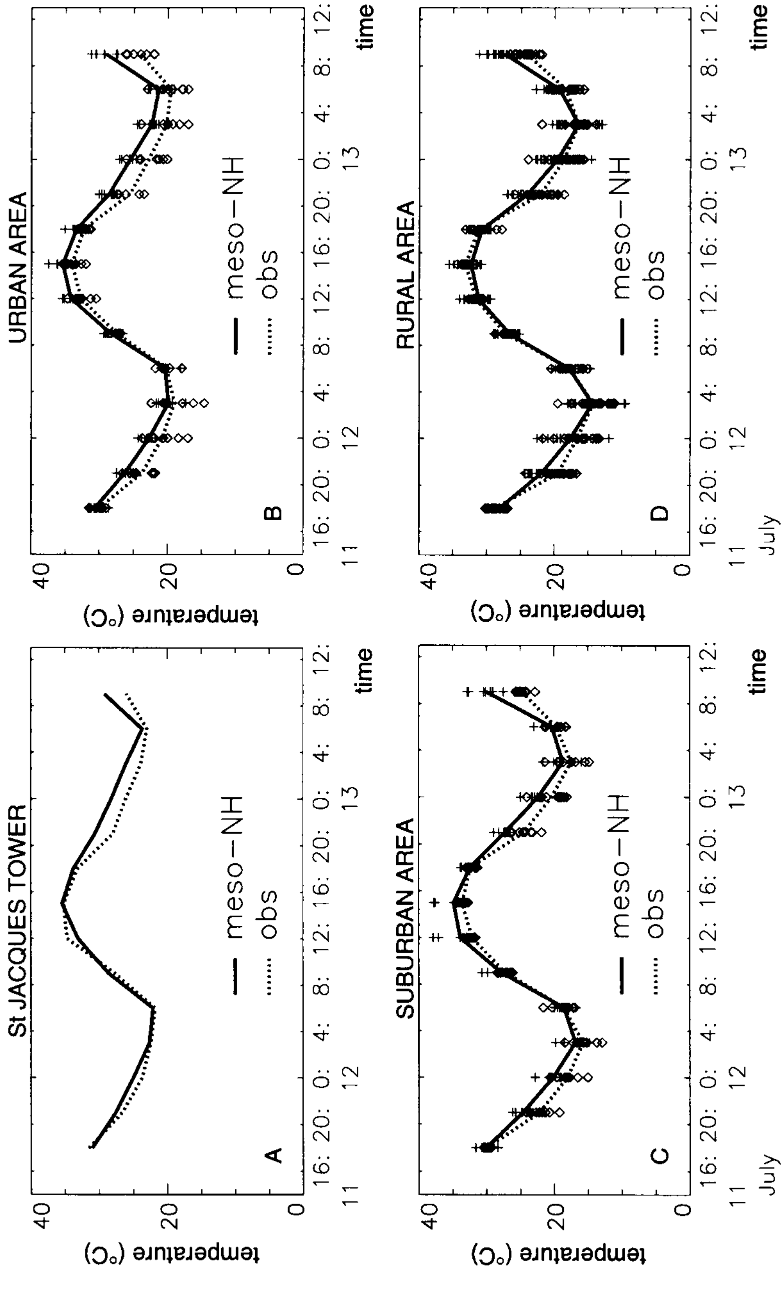

Figure 4. Comparison between the observed and simulated temperatures at 2 m, averaged by urbanization class.

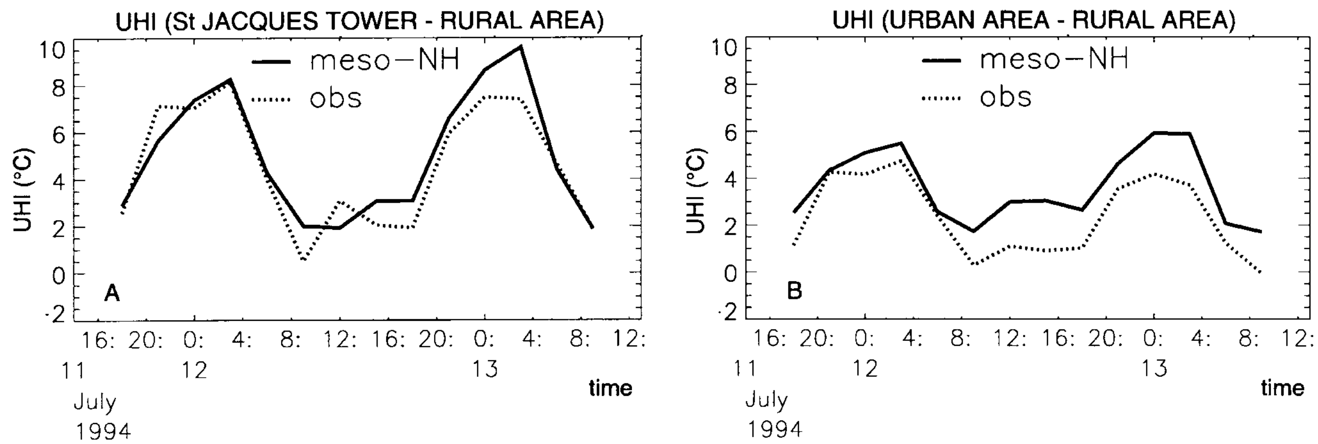

Figure 5. UHI between St. Jacques Tower and rural stations (on the left) and between urban stations and rural stations (on the right).

the urban atmosphere is much drier than the rural atmosphere and a ‘dry atmospheric moisture island’ appears above Paris (see Figure 7). It should be noted that a long spell of warm and dry weather preceded 13 July (11 days without rain). Urban materials are impervious, and the water is quickly evacuated in the cities. Consequently, sources of humidity are very weak in artificial areas, whereas the deep root zone layer still contains water in the countryside. This dry moisture island is evident during the day, when both transpiration by plants and evaporation of dew release humidity in the rural atmosphere (similar processes were documented in Christchurch, New Zealand; see Tapper, 1990).

3.3. Model performance evaluation

For temperatures and mixing ratios, the standard deviation, the root-mean square (RMS) error and the bias of observed and measured values have been computed by urbanization class (eight stations for urban area, nine for suburban area, and 20 for rural area).

The standard deviations of temperature and humidity (σ and σ_o for simulated and observed values, respectively) are presented in Figure 8. For all the classes, the standard deviation of observed temperature is larger at night, probably because of the different cooling rates of the surfaces. During the day, it stays low in rural and suburban areas, but increases in the urban area. The behaviour for moisture seems more complicated: σ_o is low everywhere at night; it stays low in the urban area and in the countryside during the day, but variability increases in the suburban regions. Since the artificial covers predominate in the urban areas (over 50%), the variability of water content in the boundary layer is limited for the urban stations (*idem* for the natural covers in rural areas). For the suburban stations, the coupling of different surface covers in variable but significant proportions may induce more variability in moisture. The model succeeds in representing the diurnal cycle of the temperature for the rural area, although it has the tendency to overestimate slightly the observations. In the urban areas, the TEB temperatures show too little variability. In the model, the initial geometric and thermal parameters of the urban covers have been specified from standard values because no adequate data base was available. A much more detailed description of the surfaces is needed in order to describe better their diversity and their different behaviours. Meso-NH largely overestimates the spatial variability of the suburban temperatures at midday. In comparing station by station, it seems that for some of the most urbanized stations of this class, the impact of the artificial surfaces is too strong.

There is good agreement between the observations and the simulations for the urban and suburban areas for moisture, but the model does not represent the strong daily deviation in the countryside. This deviation is likely to be related to the important variability of the water available in the soil. For the simulation, we used an initial field of moisture in the soil, which was homogenous. Hence, the model cannot easily represent the spatial variability observed in reality.

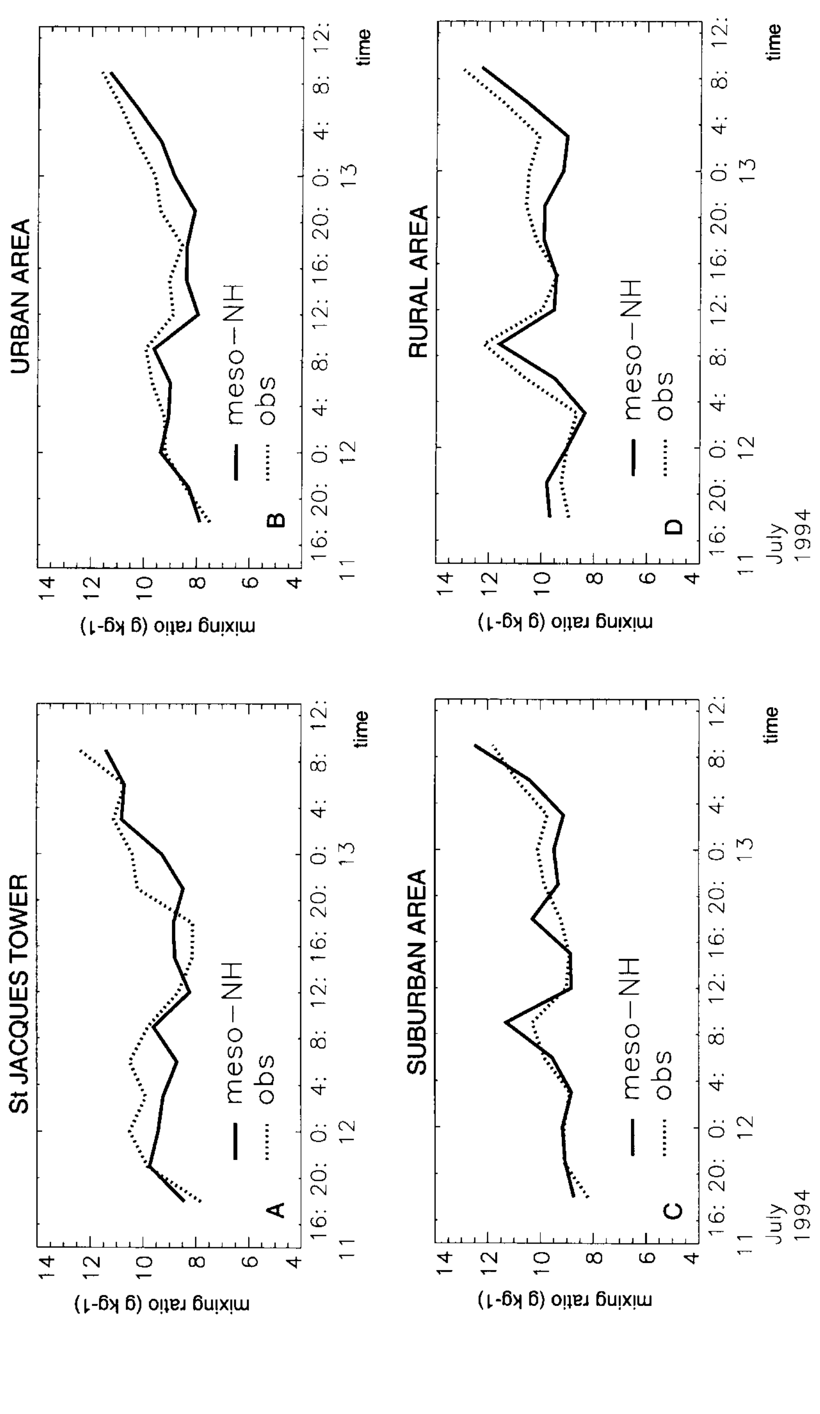

Figure 6. Comparison between the observed and simulated mixing ratios at 2 m, averaged by urbanization class.

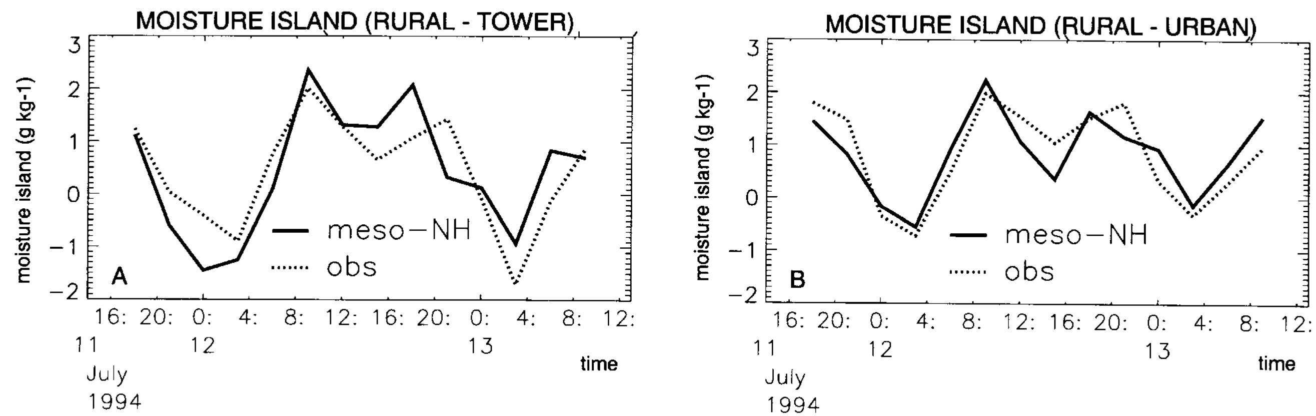

Figure 7. Moisture islands between rural stations and St. Jacques Tower (on the left) and between rural stations and urban stations (on the right).

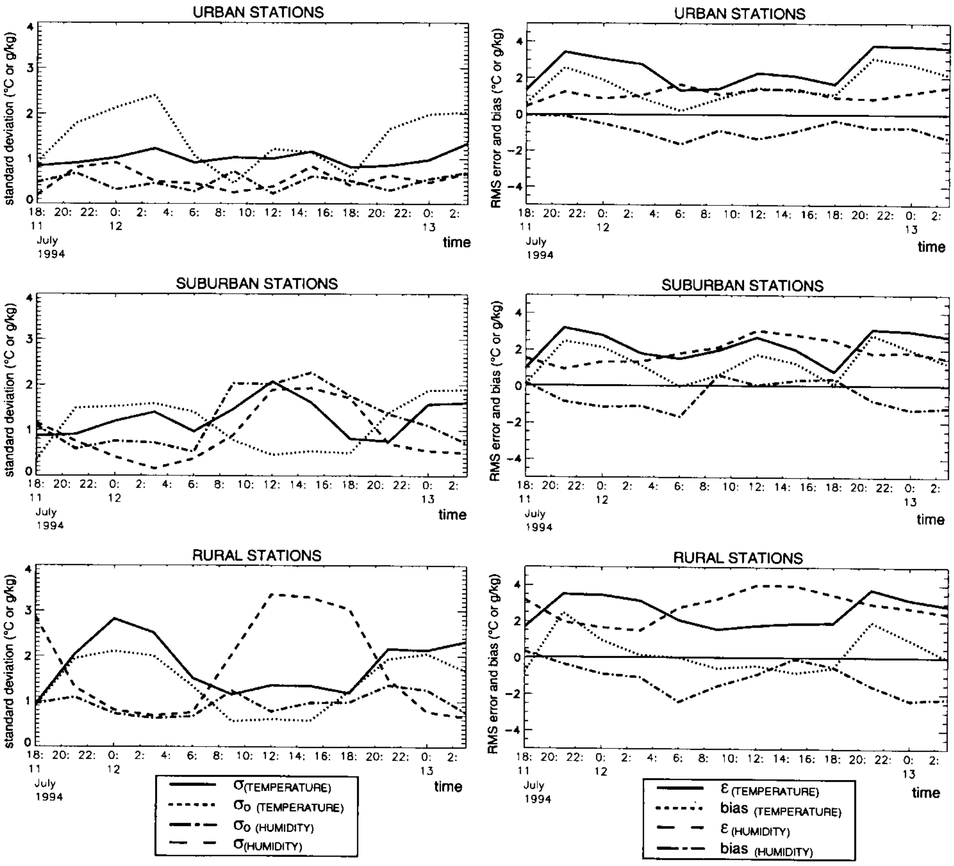

Figure 8. Left: standard deviations of observed and simulated temperatures and mixing ratios at 2 m. Right: RMS errors and biases of temperature and humidity at 2 m.

The RMS error ($\epsilon = [\sum_{i=1}^{N} \frac{(V_i - V_{io})^2}{N}]^{1/2}$, with V_i and V_{io}, respectively the simulated and observed values) and the bias (i.e., the difference between the averaged simulated temperature and the averaged observed temperature) is also plotted in Figure 8. The RMS errors for temperature and humidity show that the errors of temperature and moisture are related to the general overestimation of temperature and the underestimation of moisture by the model (see Figure 8). For both days, the bias of temperature is more intense between 1800 and 0300 UTC because the cooling rate of Meso-NH is overestimated at this time. However, even though Meso-NH succeeds in creating sufficient variability on average in the countryside, the comparison of station by station shows discrepancies. This fact induces an additional error particularly during the night. The same error exists during the day for the spatial variability of the moisture.

4. Quantification of the Urban Boundary-Layer Processes

The geometry and properties of artificial materials in urban centres induce significant climatic perturbations – namely, modification of the surface energy budget, development of the internal UBL and formation of an UHI and of an urban breeze when the conditions are favorable. These aspects are simulated and quantified below.

4.1. Local effects

A sensitivity study was conducted to estimate the influences of different physical parameters on the local meteorology. Simulations are used to investigate dynamical effects, which are influenced by physical processes and the magnitude of the perturbations. The impact of orography and urbanization in the Paris area is analyzed by comparing four different simulations: first, the outputs presented in the previous section simulate a realistic situation (simulation called S1) and have been used as a reference for the other cases. A second simulation (S2) has been performed, in which the city has been removed in order to display the effect of urbanization (the TEB scheme was replaced by the ISBA scheme in every gridbox). Third, the orography has been made uniform (120 m across the domain) with the city kept in place (simulation S3). This altitude was chosen according to the orography at the boundaries of the domain. Finally, in the last simulation (S4), both changes are made together: homogenization of orography and removal of Paris.

Some effects can be induced by both orography and the city, while others can be induced by only one or the other. The comparison of the four simulations has allowed us to estimate the impact of each one.

Previous works have addressed the local impact of surface cover and orography. Notably, Seaman et al. (1988) showed the influence of both effects and the difficulty of separating which was predominant. Recently, the dynamic influence of the orography in the Paris region has been studied (Troude, 1999; Troude et al., 2002), showing that the orography had a very small impact on the thermodynamic parameters, but the geographic situation of the city (surrounded by plateaus) induced important atmospheric vertical motions. A comparison of S1, S2 and S3 (see Figure 9) indicates that in the Paris region, urbanization was the predominant effect influencing the air temperature and mixing ratio. Neither the urban heat island nor the moisture island is disturbed in the uniform orography run, whereas the turbulent processes are markedly attenuated and disorganized in the simulation without the city. Therefore, even if the local orography is significant, the urban effects dominate the development of the turbulence in the boundary layer. Nevertheless, the vertical wind speeds imply a typical organization influenced both by orography and urbanization (see Figure 10). The comparison of simulations S1, S2 and S3 shows the different organizations of the vertical winds across the domain. In simulation S2, the vertical motions are not located at the centre of the domain (where the city was located), but along the valleys (see Figure 2). The simulation S3 (with uniform orography) also shows vertical motions where the valleys were situated because urban areas are mainly located in the valleys. The comparison of S2 and S3 shows that the two effects (orography and urbanization) are of the same magnitude in this part of the domain. In contrast, the strong up motion found in S1 and S3, which takes place just over the city centre, is induced by the Paris urban area and not by the orography. Since the aim of this work is essentially to study the urban processes, only the two first simulations (S1 and S2) will be compared further.

4.2. Surface Fluxes

Urbanization strongly modifies the surface energy budget (White et al., 1978; Grimmond and Oke, 1995; Oke et al., 1999). Here, simulated budgets in both rural and urban areas (see Figure 11) are compared, noting that no flux observations were available for the Paris region.

The comparison between both surface energy budgets shows that the daily net radiation ($Q^* = Q_E + Q_H + \Delta Q_S$) is slightly greater in the urban area than in the countryside. The three-dimensional geometry of the urban canyons induces opposite effects, which are considered by the TEB scheme. On the one hand, trapping of the incident solar radiation and longwave emission of the surfaces is found. On the other hand, shade effects directly proportional to the aspect ratio of the streets (height of the building to width of the street) are observed. The higher values of Q^* simulated in the city centre are probably explained by the predominance of the trapping effect. At the St Jacques tower station, the most significant output flux is the storage heat flux (ΔQ_S), as in Tucson (Grimmond, 1991), which reaches here 450 W m^{-2} at 1200 UTC. In the TEB scheme, the urban surfaces are specified as concrete surfaces for Paris. Consequently, they have a strong conduction capacity. In addition, the height of buildings (50 m in the city centre) means the total area available for storage (walls, roads and roofs) is largely and much more important than in the countryside. The sensible flux (Q_H) is also important in the city, since the latent flux (Q_E) is close to zero. In this part of Paris, the vegetation cover is very small (only 10 percent), which limits the evapotranspiration process. In contrast, Q_E predominates at the rural sites and reaches 450 W m^{-2} at about 1200 UTC. Since the vegetation cover is very extended in these areas, the transpiration of plants utilises the greater part of the incident energy and produces significant latent fluxes during the day.

At night, all the fluxes are negligible in the country, corresponding to very low energy exchanges between the surface and atmosphere. In contrast, the urban budget exhibits negative values of ΔQ_S (directed towards the atmosphere) and a positive sensible flux. The storage heat flux releases energy to the atmosphere and creates a small upward sensible flux after sunset, which is sufficient to maintain turbulence above.

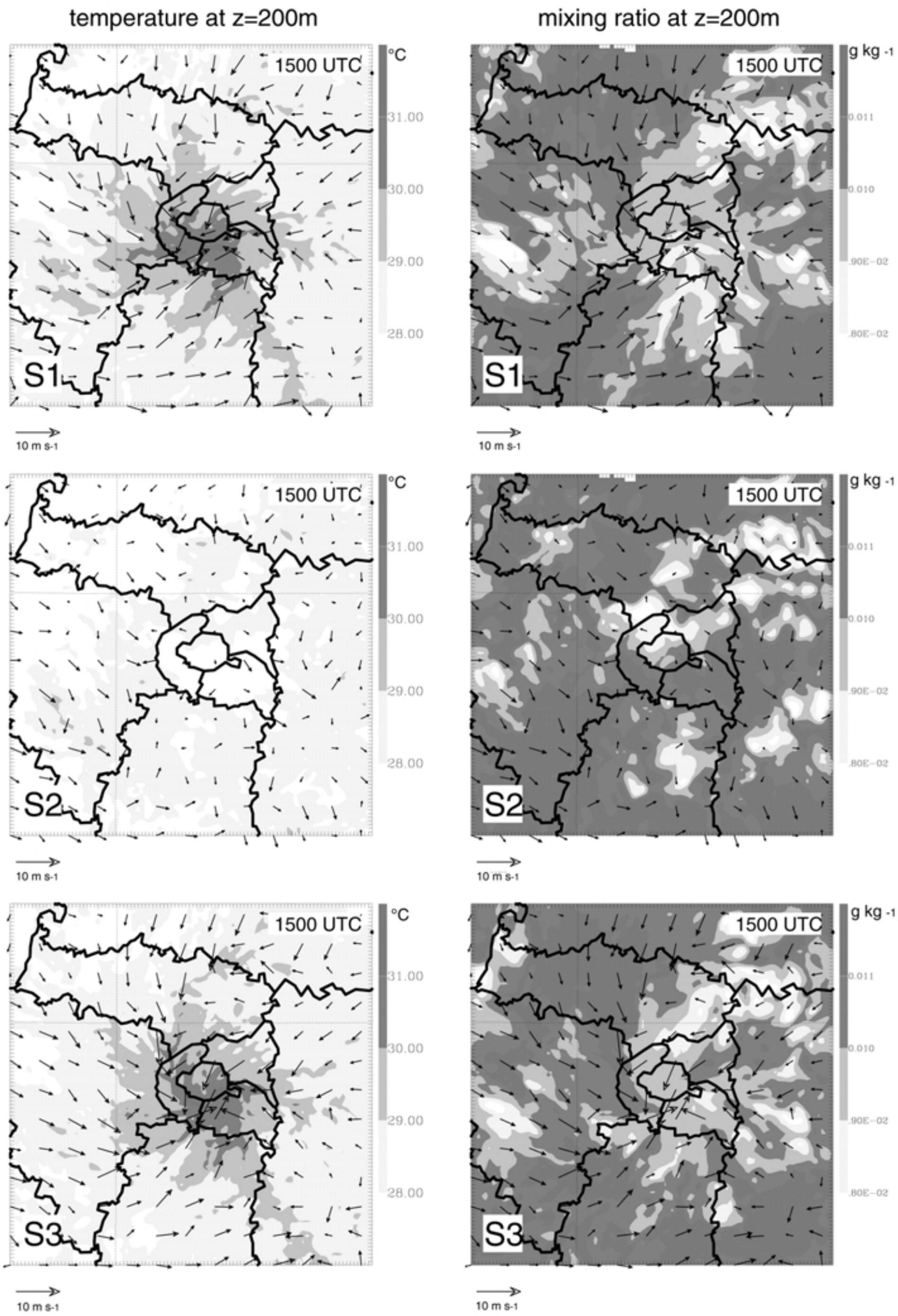

Figure 9. Comparison between the fields of temperature (on the left) and mixing ratio (on the right) at 200 m, 12 July 1994 at 1500 UTC for the three simulations S1 (reference), S2 (without Paris) and S3 (with uniform orography). The arrows represent the horizontal wind at the same altitude.

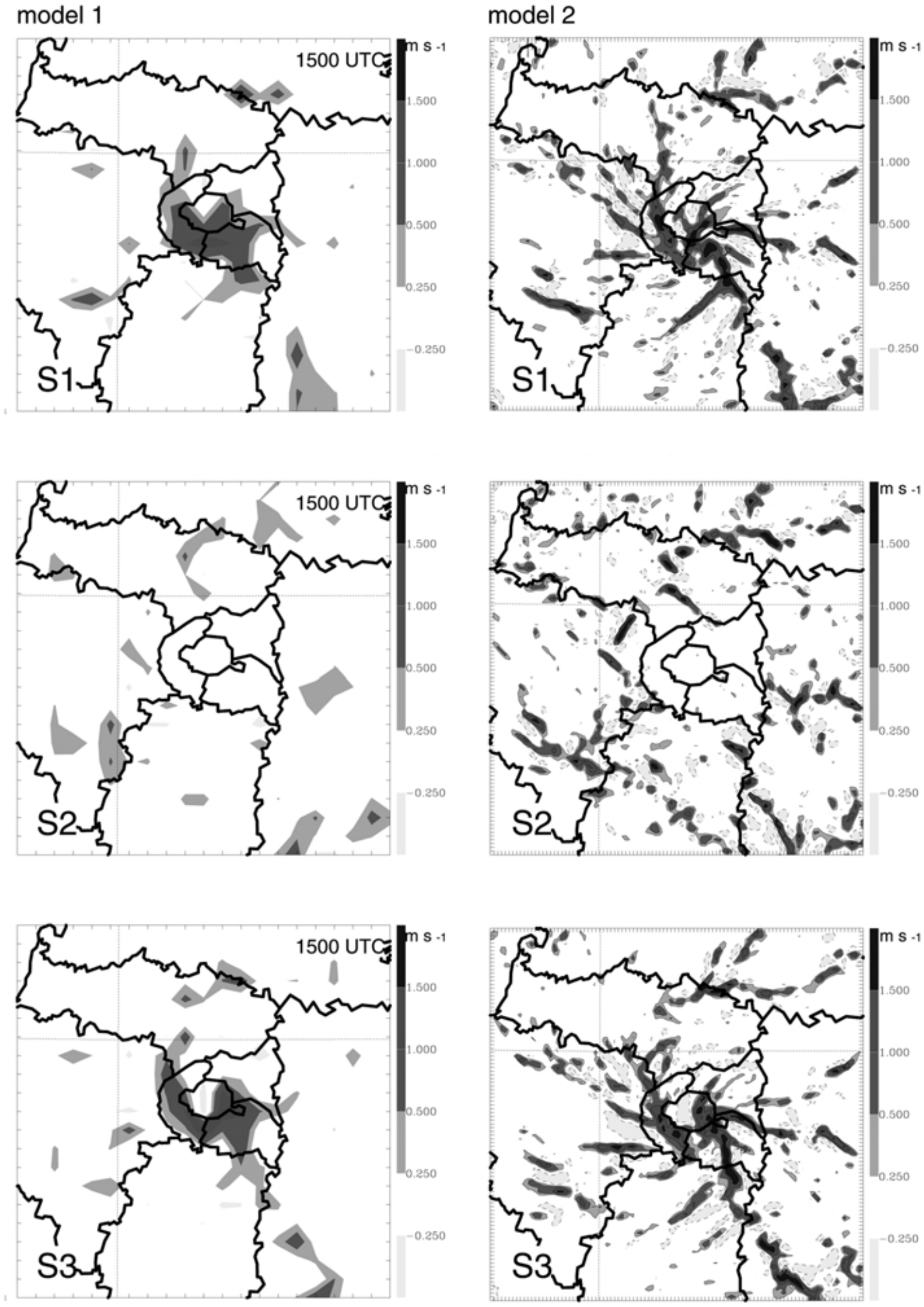

Figure 10. Horizontal fields of vertical wind speed at 200 m, 12 July 1994 at 1500 UTC. On the left: Field obtained by model 1, corresponding to a spatial average of model 2. On the right: Field obtained by an average of the outputs of model 2 every 10 min between 1400 UTC and 1600 UTC.

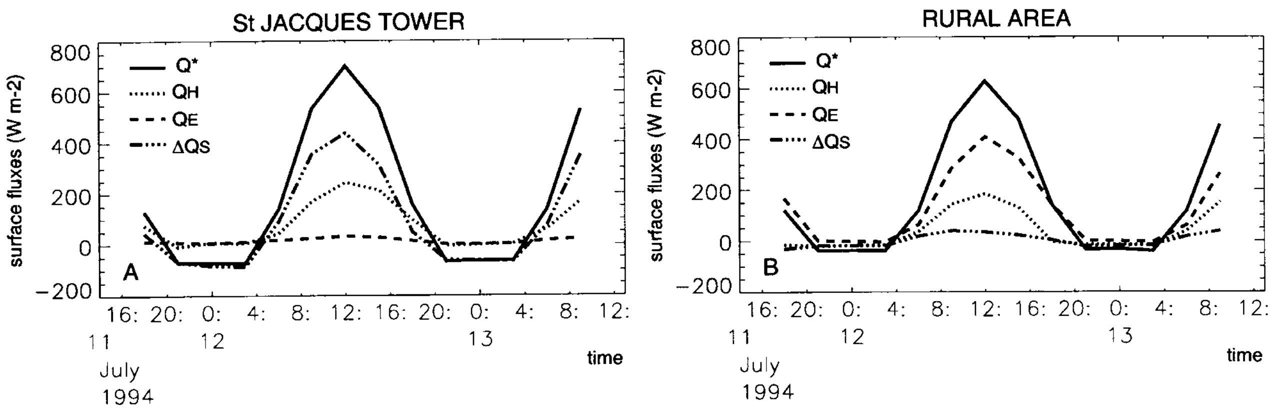

Figure 11. Simulated surface energy budgets for the St. Jacques Tower and the rural stations. The components are the net radiation (Q^*), the sensible flux (Q_H), the latent flux (Q_E) and the heat storage flux (ΔQ_S).

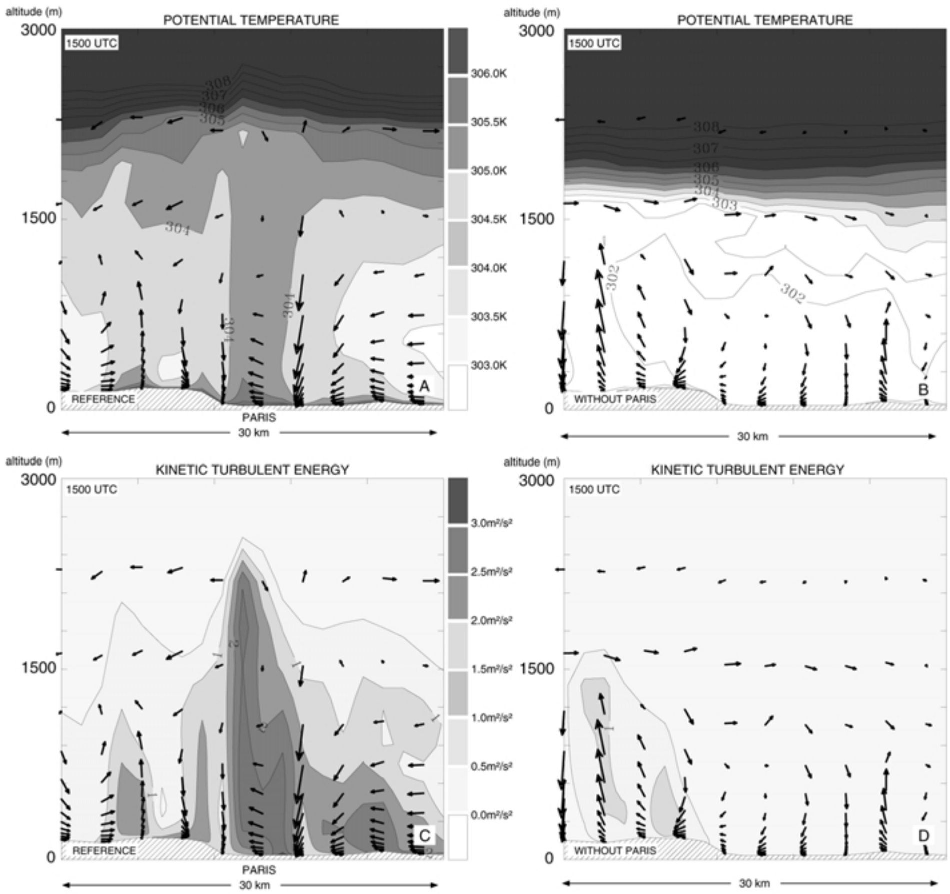

Figure 12. Vertical section of potential temperature and kinetic turbulent energy, 12 July 1994 at 1500 UTC, for the simulations S1 (realistic case) and S2 (without Paris). The arrows represent the wind in the section.

4.3. Boundary-layer structure

The structure of the UBL depends on the surface energy budget. Two vertical sections of potential temperature and kinetic turbulent energy have been plotted and compared for both simulations, at 1500 UTC and 0300 UTC (Figures 12 and 13, respectively). The daily UBL becomes strongly unstable and its depth reaches 2500 m at 1500 UTC in simulation S1 (see Figure 12). When there is no city, the UBL only reaches 1800 m. The observations of the ECLAP campaign (which has taken place in winter) have also shown an UBL more turbulent and unstable in the Paris region than in the countryside (Dupont et al., 1999). The kinetic turbulent energy shows that very turbulent processes are induced above Paris (see Figure 12) due to the warming and heat storage. Furthermore, the mean vertical speed above the city is positive and reaches 1 m s^{-1} at 1500 UTC (see Figure 10).

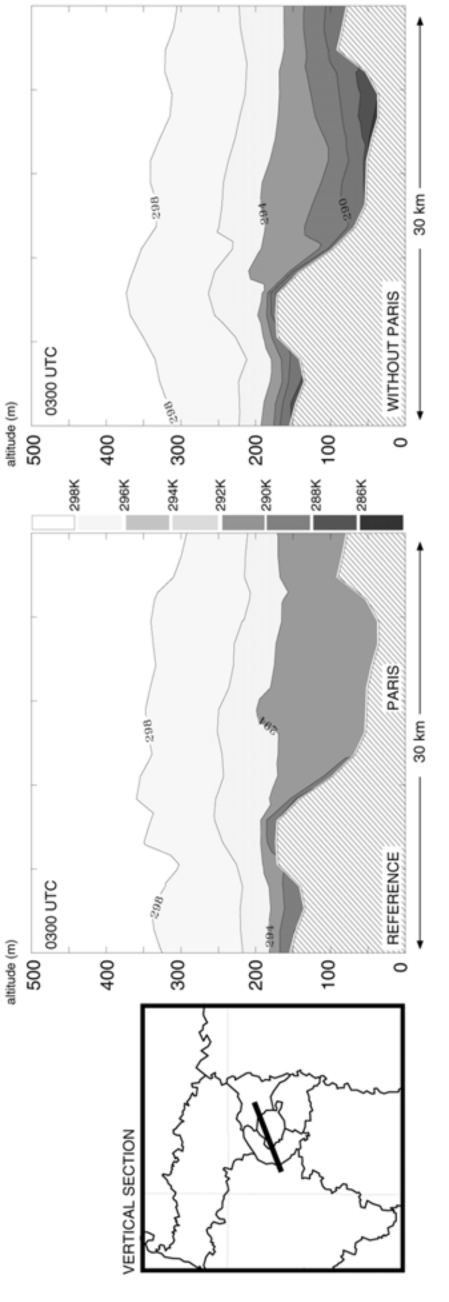

Figure 13. Vertical section of potential temperature, 12 July 1994 at 0300 UTC, for the simulations S1 (realistic case) and S2 (without Paris).

At night (see Figure 13), the simulation S2 is characterized by a rural boundary layer that becomes strongly stable because of the fast cooling of the vegetation cover. Yoshikado (1992) found a similar boundary-layer structure above the rural areas of the Tokyo region. In contrast, since a small upward turbulent heat flux continues above the urban areas, the nocturnal UBL remains neutral and never becomes stable. A similar phenomenon was also noted during the ECLAP experiment (Dupont et al., 1999) and in Zurich (Rotach, 1995). Furthermore, kinetic turbulent energy is still produced above Paris, but disappears in the simulation without the city (not shown).

4.4. UHI and the establishment of a strong urban breeze

Given the comparison between simulations S1, S2 and S3, the UHI process seems directly induced by the city. In the model, when Paris is removed, the horizontal temperature gradient disappears (as for the episodes of ECLAP analysed by Troude, 1999) because the rates of warming and cooling are the same across the whole domain. Even if the dailytime UHI is weaker than during the night, it may induce more intense local circulations over the city as recently documented in Atlanta by Bornstein and Lin (2000). In some meteorological conditions (a strong temperature gradient and a weak wind in the domain), an urban breeze is created, corresponding to an atmospheric circulation coupling convergence near the surface to divergence at a high altitude. To study this process, horizontal winds of both real and rural simulations have been compared at 1500 UTC for altitudes of 200 m and 2000 m. To make the comparison easier, the difference between the horizontal wind of S1 and the horizontal wind of S2 has been computed and plotted. At 200 m, a strong convergence of about 5–7 m s^{-1} appears over Paris, and at 2000 m a strong divergence occurs over the surrounding countryside (see Figure 14). This result allows one to demonstrate both that an urban breeze takes place and that it is directly induced by the city (such a process does not exist in the simulation without Paris). One can note that in spite of the strong roughness of the city centre, the strongest winds occur above the urban and suburban areas of Paris. This observation is in agreement with previous works in St Louis (project METROMEX, Shea and Auer, 1978; Wong and Dirks, 1978). They have shown that the temperature anomaly was the major effect under steady conditions and that it induced stronger wind speeds over the city. During the night, the surface fluxes are too weak and the inversion above the neutral urban layer is too stable to create the same urban breeze.

5. Other Cases

Many previous works have studied the influence of the synoptic wind on the UHI circulation intensity and pattern (Shea and Auer, 1978; Wong and Dirks, 1978). It

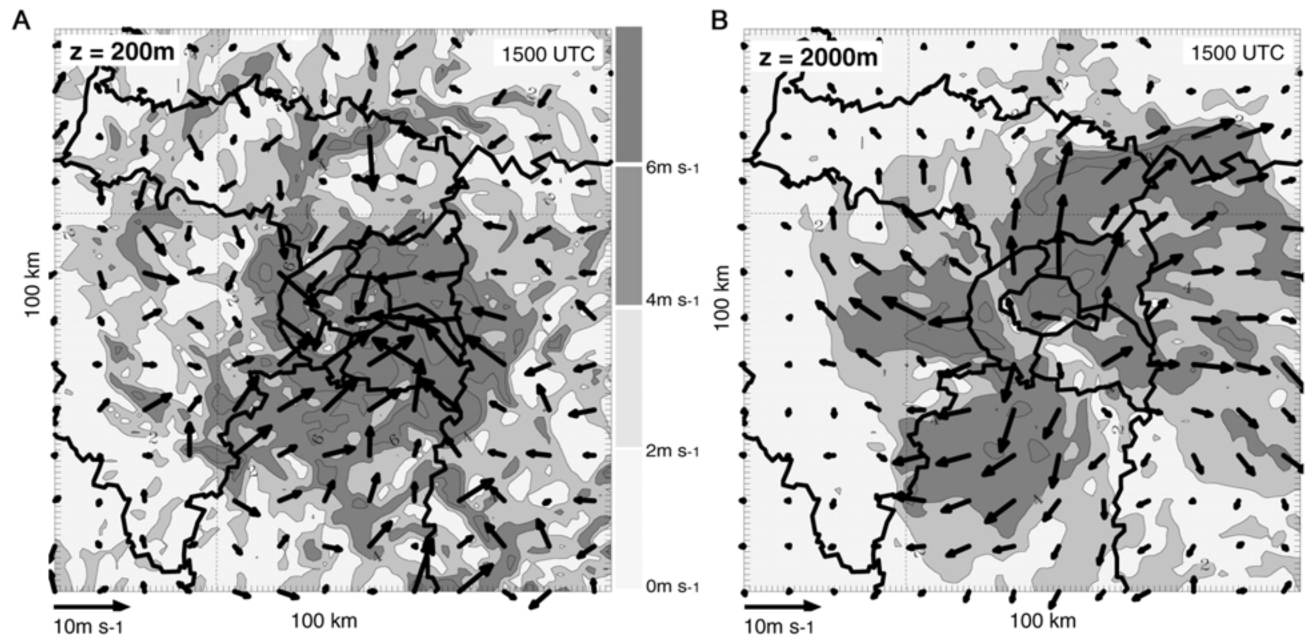

Figure 14. Difference of horizontal wind between the simulations S1 (realistic case) and S2 (without Paris), 12 July 1994 at 1500 UTC. Both wind direction (arrows) and magnitude are displayed. A: Near the surface. B: At the boundary-layer top.

appeared that the thermal effect reinforced the wind over the city (creating the urban breeze) under a weak synoptic flow. In contrast, with a strong flow, the roughness weakened the wind over the city and the UHI circulation disappeared. Shea and Auer (1978) have shown also the establishment of a warm urban plume for a flow around 8 m s^{-1}. Numerical works (Sawai, 1978; Sharan, 2000) have shown that without a synoptic wind, the two cells of the breeze were symmetric and stayed above the city. With a weak prevailing flow (around 2.5 m s^{-1}), a warm air mass was displaced downwind of the city with an associated shift of the ascending flow out of the city.

For our study, three other episodes, corresponding to different synoptic conditions, have been considered. Interesting results have been found concerning the local wind circulations around the city, in agreement with the works presented previously. First, the outputs of the 3 April 1995 show a similar case of an urban breeze at 1500 UTC (see Figure 15). As in the July episode, the meteorological conditions (particularly the mean wind coupled with a strong UHI) favour strong vertical winds and the formation of a breeze. In spite of magnitudes around 5 m s^{-1}, the synoptic wind appears disorganized, especially in the south; in the north of the domain, the westerly wind is more marked. So the core of the urban breeze, namely the location of strongest up motion, is slightly tilted to the east of the city centre. The 24 March 1995 case presents a different situation: the synoptic wind in the domain reaches 7 m s^{-1} in the afternoon with a marked orientation. Consequently, the urban breeze cannot develop and is replaced by an urban plume along the prevailing wind (see Figure 16). Finally, the last example of the 12 April 1997 (not shown) does not present any typical circulation and thermodynamic fields. For this episode, the wind reaches 6–7 m s^{-1} in the afternoon, and is probably too strong to generate a breeze.

6. Conclusion

The warm and dry episode of the 12 July 1994 presents favorable conditions over Paris for evaluating both the TEB scheme and the Meso-NH model. The Meso-NH results have been shown to be very satisfactory; the trends and the magnitudes of temperature and humidity have been simulated correctly. Observed fluxes would be necessary to complete the validation of the model. This study has investigated some specific UBL processes. The urban geometry and artificial material properties have been shown to induce large modifications of surface fluxes when compared with modelled rural exchanges. Indeed, the heat conduction flux towards buildings becomes the major factor of the surface energy budget: the sensible heat flux stays positive because of important heat storage, and the latent flux is almost zero given the small vegetation cover. These anomalies disturb the local climate. Firstly, an UHI is simulated above Paris (which corresponds to the observations) and reaches 8 °C at night. Secondly, the UBL presents strong instability and turbulence during

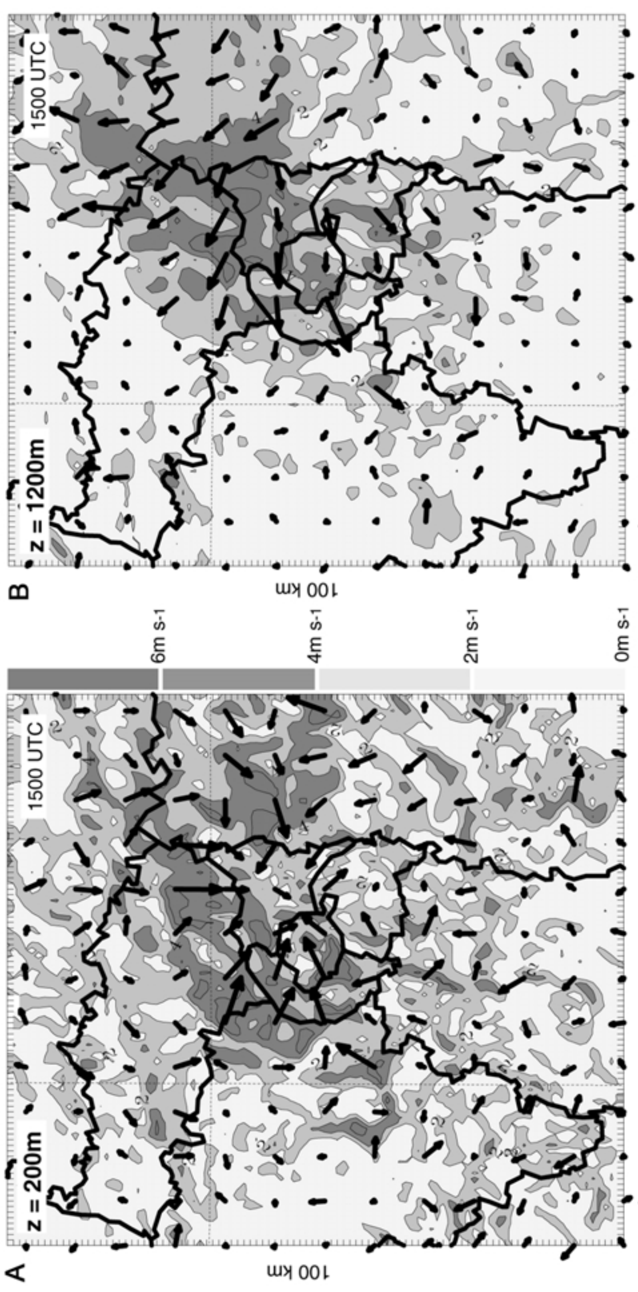

Figure 15. Difference of horizontal wind between the realistic simulation and the simulation without Paris, 3 April 1995 at 1500 UTC. Both wind direction (arrows) and magnitude are displayed. A: Near the surface. B: At the boundary-layer top.

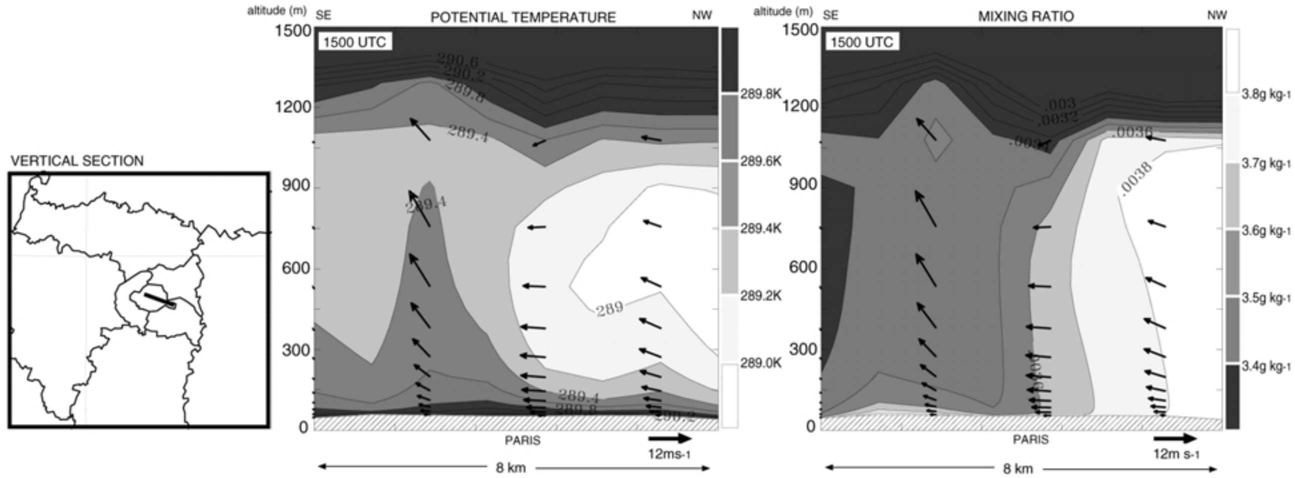

Figure 16. Vertical section of potential temperature and mixing ratio, 24 March 1995 at 1500 UTC, for the simulations S1 (realistic case) and S2 (without Paris). The arrows represent the wind direction in the section.

the daytime. At night, it becomes neutral but never stable, as was measured in Zurich by Rotach (1995). Lastly, the different cases studied have allowed greater insight into the necessary conditions to create special urban atmospheric circulations for a city of the size of Paris and without important orographic effects. For a weak and disorganized synoptic wind below 5 m s^{-1}, the urban breeze can take place freely in the afternoon, with the simulations showing vertical winds around 1 m s^{-1}. The horizontal wind reaches 7 m s^{-1} over the suburban areas around Paris, and the circulation at the boundary-layer top extends outwards to 50 km. In such conditions, the pollutants emitted from the city can be advected toward the countryside. If the mean wind is more intense, namely around 7 m s^{-1}, the UBL becomes an urban plume oriented in the direction of the flow.

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