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Sea-town interactions over Marseille: 3D urban boundary layer and thermodynamic fields near the surface

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With 6 Figures

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Summary

3D numerical simulations with the Meso-NH atmospheric model including the Town Energy Balance urban parameterization, are conducted over the south-east of France and the one million inhabitants city of Marseille in the frameworks of the ESCOMPTE-UBL program. The geographic situation of the area is relatively complex, because of the proximity of the Mediterranean Sea and the presence of numerous massifs, inducing complex meteorological flows. The present work is focused on six days of the campaign, characterized by the development of strong summer sea-breeze circulations. A complete evaluation of the model is initially realized at both regional- and city-scales, by using the large available database. The regional evaluation shows a good behavior of the model, during the six days of simulation, either for the parameters near the surface or for the vertical profiles describing the structure of the atmosphere. The urban-scale evaluation indicates that the fine structure of the horizontal fields of air temperature above the city is correctly simulated by the model. A specific attention is then pointed to the 250-m horizontal resolution outputs, focused on the Marseille area, for two days of the campaign. From the study of the vertical structure of the Urban Boundary Layer and the thermodynamic fields near the surface, one underscores the important differences due to the regional and local flows, and the complex interactions that occur between the urban effects and the effects of sea breezes.

1. Introduction

The parameterization of the urban processes at the canopy scale is of prime importance to model in a realistic way the regional and local meteorology close to the cities. Such processes can play a significant role on the vertical structure of the atmosphere and on the atmospheric circulations. According to the local environment, complex interactions can occur between urban, topographic, synoptic or maritime effects. Notably, some numerical works underscore the impact of the urban areas on the land-sea breeze circulations: Tokyo (Yoshikado, 1992; Kusaka et al., 2000), Athens (Martilli et al., 2001), Osaka (Ohashi and Kida, 2002). These studies are especially interesting for the understanding of the circulation of the air pollutants, giving the fact that numerous cities are located on coastal areas. However, only few studies focus on the coupling dynamics of urban and sea breeze in the boundary layers in details at the urban scale. In a 2D atmospheric model using a state of the art urban scheme (Martilli et al., 2002), Martilli (Martilli, 2003) showed that the city presence tends to slow the sea breeze front progression inland. The objective here is to study these complex interactions, at the urban scale, but with a 3D atmospheric model. Furthermore, a realistic and intensively observed case is treated (Sections 2 and 3). Comparison with data is done extensively at regional scale (Section 4.1) before the simulated Urban Boundary Layer is evaluated

(Section 4.2) and synoptic and mesoscale interactions with sea, city and topography are analyzed in the last section.

2. Experimental context

2.1 Experimental domain

The field ExperimentS to COnstraint Models of atmospheric Pollution and Transport of Emissions (ESCOMPTE) experiment (Cros et al., 2004) is a large experimental campaign that took place in the Provence-Alpes-Côte d'Azur region, in the south-east of France, during summer 2001. The main objective was the study of the dynamical and chemical processes at the origin of the summertime photochemical pollution often observed in this area. The Urban Boundary Layer (UBL) program (Mestayer et al., 2005) was associated to ESCOMPTE in order to specifically document the surface processes and the 4D structure of the atmosphere over the city of Marseille. The experimental area has a great geographic diversity. It is skirted southward by the Mediterranean Sea and the presence of the Alps and the Rhône Valley to the north gives place to specific synoptic situations. Locally, the topography disrupts considerably the displacement of air masses. The Luberon mountain, located northward, reaches about 1100 m, and Marseille is also framed by the Etoile (600 m) and the Sainte-Baume (1000 m) massifs, northward and eastward respectively. Lastly, the surface is very heterogeneous: urban and industrial covers, cultures, forests, garrigues and water areas. In summer, the climate is very sunny and the maximum air temperatures reach 30 to 35 °C inland and 25 to 30 °C on the littoral. Sea breezes frequently take place during the afternoon. They blow from west or south-west according to the orientation of the coastline. Situations of Mistral (strong wind of the north-west along the Rhône valley) and south-east winds also affect the domain.

2.2 Observational networks

The permanent observational systems worked continuously during the campaign, and were reinforced in case of Intensive Observational Periods (IOP). At the regional scale (see Fig. 1b),

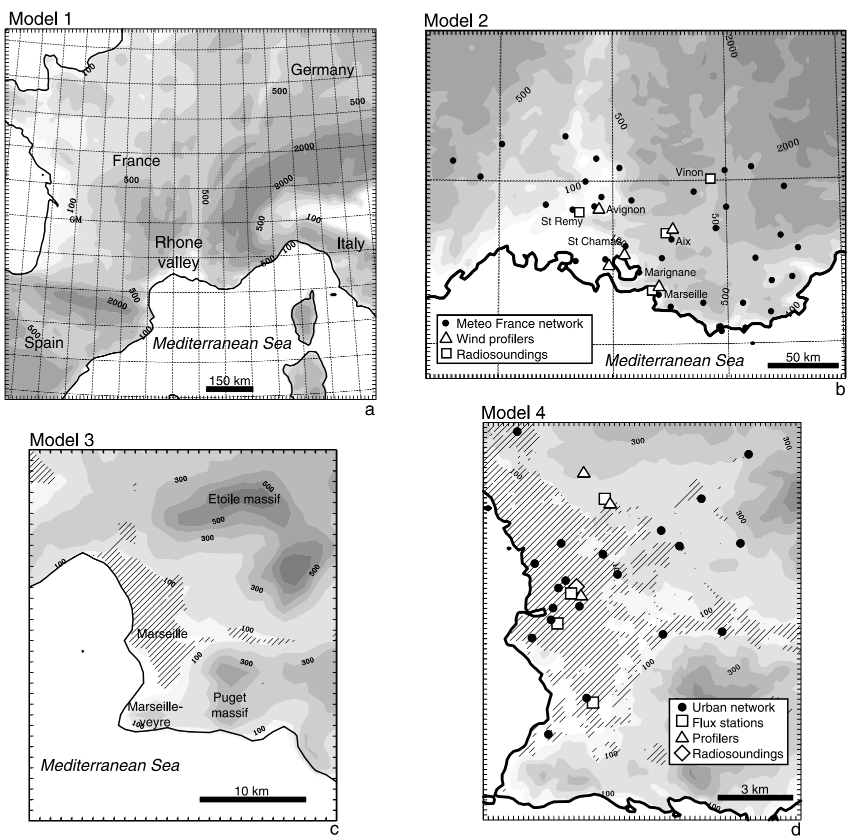

Fig. 1. Presentation of the four modeling domains with topography. For the two last models, the urbanized areas of Marseille are represented by hatchings. On models 2 and 4, are labeled the regional and urban observational networks, respectively

36 stations of the Météo-France operational network recorded 2-m air temperature, relative humidity, pressure and 10-m wind components. Numerous wind profilers (sodars, UHF and VHF radars, and lidars) were deployed to document the vertical structure of the atmosphere. This was supplemented by radiosoundings, and instrumented aircrafts and balloons. Supplementary observations were conducted at the city-scale (Fig. 1d) in the frameworks of the UBL program: 20 sensors of temperature and humidity located inside the streets of Marseille (Pigeon et al., 2005), four wind profilers, four flux stations, and aircraft measurements above the city.

2.3 Meteorological situation

This study is focused on the second IOP of the campaign, which occurred between the 21 and the 26 June 2001. It was divided in two distinct periods: (1) IOP 2a (21–23 June) is characterized by very sunny conditions and a strong north-west Mistral wind, which blows in the most part of the domain, excepted on the eastern coast (east of Marseille). At daytime, a western sea breeze is observed on the coastline. (2) IOP 2b (24–26 June) is characterized by the weakening of Mistral, which favors the intrusion of south or south-west sea breezes inland.

3. Numerical setup

The 3D simulations were realized with the Meso-NH non-hydrostatic atmospheric model (Lafore et al., 1998). Four grid-nested models (presented in Fig. 1), with successive horizontal resolutions of 12 km, 3 km, 1 km and 250 m, are used to cover all scales, from synoptic- to city-scale. Their initial conditions and the model 1 boundary conditions are defined from the European Center Mesoscale Weather Forecasting (ECMWF) analyses. The vertical grid, common to all the models, contains 52 levels more stretched with the altitude. The Atmospheric Boundary Layer (ABL) is finely described with 28 levels in the first 1500 m. Note that the first atmospheric level is located 6 m above the canopy (i.e. above the top of the vegetation and the top of the buildings). The turbulence scheme (Cuxart et al., 2000) uses a mixing length calculated according to the 1D method of Bougeault and Lacarrere (1989) for the first three models, while the high resolution of the last one requires a 3D calculation, based on the Large Eddy Simulation parameterization of Deardorff (1974). Sea Surface Temperature comes from NOAA AVHRR satellite images.

Two surface schemes are implemented in Meso-NH: the Interaction Soil Biosphere Atmosphere (ISBA) (Noilhan and Planton, 1989) and the Town Energy Balance (TEB) (Masson, 2000) schemes. The first one parameterizes the interactions between the natural soil, the vegetation and the atmosphere, while the second one is specifically dedicated to the exchanges between the urban canopies and the atmosphere. Both of them require a good knowledge of the land covers and the surface characteristics. The land cover map is provided by the CORINE Land Cover Classification (CEC, 1993) at 1 km resolution, and is refined on Marseille area by using the database of the Regional Center of Geographic Information (CRIGE). The later dates from 1999 and its resolution is 30 m. The parameters relative to the soil, the vegetation, the water and the urban surfaces come from ECOCLIMAP (Masson et al., 2003). Note that the system ISBA-TEB has already been validated off-line against the energy fluxes measured in the city centre of Marseille (Lemonsu et al., 2004).

4. Evaluation of the model

The IOP 2a and IOP 2b are simulated independently from one another, by applying a spin-up period of 12 hours for each of two. The evaluation of the model was done against a large number of observations. Here are presented some of them. Note that the evaluations use the outputs of the second model (3-km horizontal resolution) for the regional-scale, and those of the last model (250-m resolution) for the city-scale.

4.1 Regional evaluation

The measurements of the Météo-France stations are compared with the air temperature and specific humidity interpolated at 2 meters, and the wind speed interpolated at 10 meters for the stations located inside the Rhône Valley (Fig. 2). The statistical scores are also presented in Table 1. The temporal evolution of the wind speed (Fig. 2c) expresses the transition from a

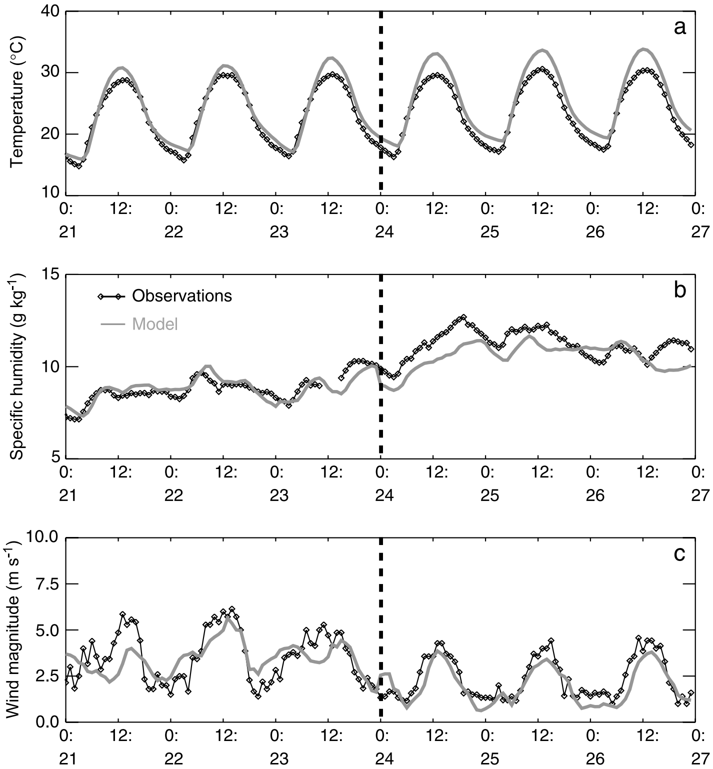

Fig. 2. Comparison between modeled and observed 2-m air temperature and specific humidity and 10-m wind speed. 2-m air temperature and specific humidity are averaged from the 36 stations, when the 10-m wind speed is only averaged from the stations of the Rhône Valley (the Rhône Valley is labeled on Fig. 1a). The dotted line separates the IOP 2a and IOP 2b

Table 1. Statistical scores, calculated for the complete IOP 2, associated to the meteorological parameters provided by the operational network, and the ABL heights estimated from the radiosoundings of Aix les Milles

	Unit	RMSE	Bias	$z_{i\ avg}$
Operational network				
2-m temperature	K	3.05	+1.4	
2-m specific humidity	$g\,kg^{-1}$	1.72	+1.2	
10-m wind speed	$m\,s^{-1}$	1.82	−0.6	
Radiosoundings				
Nocturnal ABL height	m	42	+6.4	261.6
Morning ABL height	m	121	−93.2	480.0
Daytime ABL height	m	79	+37.0	971.6

strong Mistral during the IOP 2a to a sea-breeze situation during the IOP 2b. This is associated to a general increase of the temperature and the humidity (Fig. 2a and b). These tendencies are also reproduced by the model, but the temperature is overestimated during IOP 2b, especially at daytime around noon. The specific humidity is well simulated but a little bit underestimated. From the wind profiler measurements and the model outputs (by using the rotation of the wind direction), we estimate when the sea breeze starts and how it propagates inland during the IOP 2b. According to the profiler located at Saint-Chamas (west of Marseille, at about 21 km from the coast), it is simulated 1 hour earlier at the first day but occurs only 15 min later than in the observations, for the 25 and the 26 June. The sea breeze, which is observed between 0800 and 0830 UTC at Saint-Chamas, reaches Avignon (north of Saint-Chamas, at about 44 km inland) between 1000 and 1030 UTC, this is correctly simulated by the model. Under such condition, a large part of the region is under influence of the sea breeze. Note that the city of Marseille has not any impact neither on the extension nor on the intensity of the sea breeze. Radiosondes were launched from different sites. Table 1 presents the statistical results for the radiosoundings of Aix en Provence (labeled on Fig. 1). The top of the ABL (z_i) is estimated from the potential and the mixing ratio profiles for both sonde data and model outputs. The averaged ABL top ($z_{i\ avg}$), the RMSE and the bias are calculated from the nocturnal (around midnight), the morning (around 0600 UTC) and the midday radiosoundings for the whole IOP 2a and IOP 2b. In the morning, the modeled ABL are most of the time underestimated in comparison to the observations, especially during IOP 2b, while the

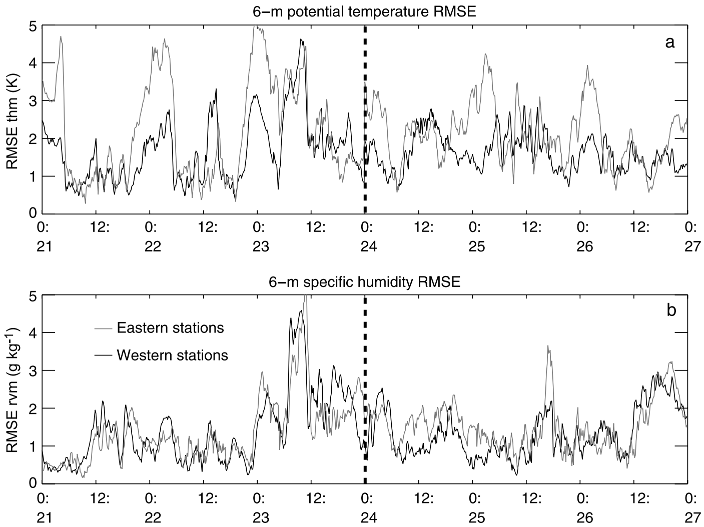

Fig. 3. Temporal evolution of the RMSE for the 6-m air potential temperature and specific humidity. The RMSE is calculated separately from the western and eastern stations of the urban network (labeled on Fig. 1)

vertical structure and the stability of the ABL is correctly reproduces at night and during daytime.

4.2 City-scale evaluation

A direct comparison between the air temperatures and humidities recorded by the 20 sensors located inside the streets of Marseille and the parameters diagnosed at 6 meters above the ground from the Meso-NH outputs is conducted. Figure 3 shows the temporal evolution of the RMSE of both temperature and humidity during the modeling period. The eastern and western stations (7 and 13 stations, respectively), for which the temperature evolutions are different, are presented separately. For the western stations (and especially in the urban dense area) the temperature is better simulated than in the east part of the domain, where the stations are farther from the coast and where the topography is important. The model does not succeed in reproducing the high nocturnal cooling in these areas, while it is very realistic in the city centre. The statistical results show that, except in the morning of the 23 June (because the flow turns to south too early in the simulation), the specific humidity is correctly simulated.

5. Sea-town interactions

The extensive evaluation of the Meso-NH simulations at both meso- and city-scales confirms the realism of the numerical results. The simulations of the model at 250 m of resolution allow to interpret the complex daytime temperature patterns interpolated from Pigeon et al. (2005) by using the 20 sensors. A specific attention is pointed to the outputs of the 22 and 26 June 2001, in order to illustrate two different situations. The fields of potential temperature near the surface and the structure of the UBL are largely influenced by the regional condition and the local winds, especially the sea-breeze circulations.

The 22 June illustrates the typical regional situation observed during the IOP 2a. In this case, west and south-west sea breezes, which occur in the afternoon, are limited to the coastal areas, while the Mistral blows inland in the most part of the domain. At the city-scale, the temperature and humidity fields near the surface underscore similar organizations. Oriented from the west above Marseille, the sea breeze corresponds to an air entrance from the sea, associated to colder temperatures (see the observed field on Fig. 4a and the simulation on Fig. 5a) and higher humidities (not shown). Its horizontal extension inside the city is weaker in the north part of Marseille than in the south part, because it is countered by the strong north-west flow. However, note that the Mistral, which reaches about 15 m s^{-1} northward of Marseille, is slowed down by the roughness of the city and decreases to 6–7 m s^{-1}. The vertical section of mixing ratio (crossing Marseille from south to north) also underlines the maritime intrusion (Fig. 6a), as an internal layer of about 200 m in the north of the Marseilleveyre massif. Elsewhere, the UBL is better developed. It reaches about 1250 m over the city core and 1100 m over the north districts.

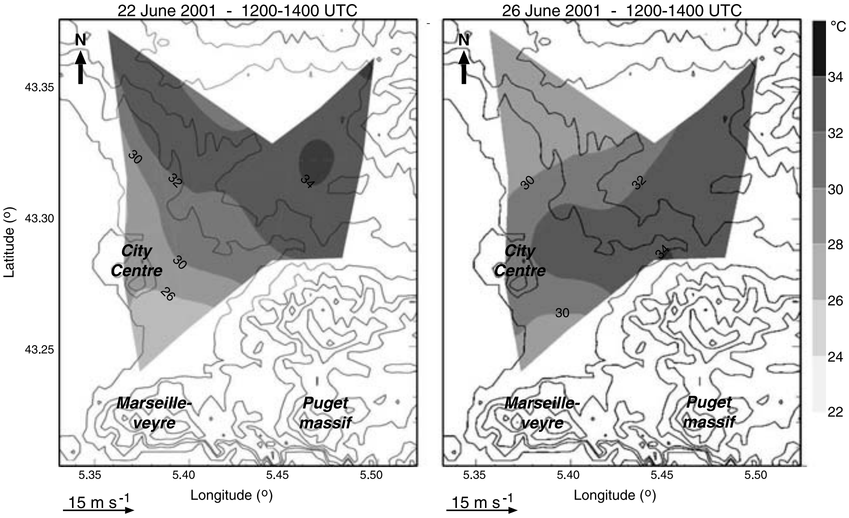

Fig. 4. 6-m potential temperature field integrated between 1200 and 1400 UTC for the 22 and the 26 June 2001, from the observations of the urban network

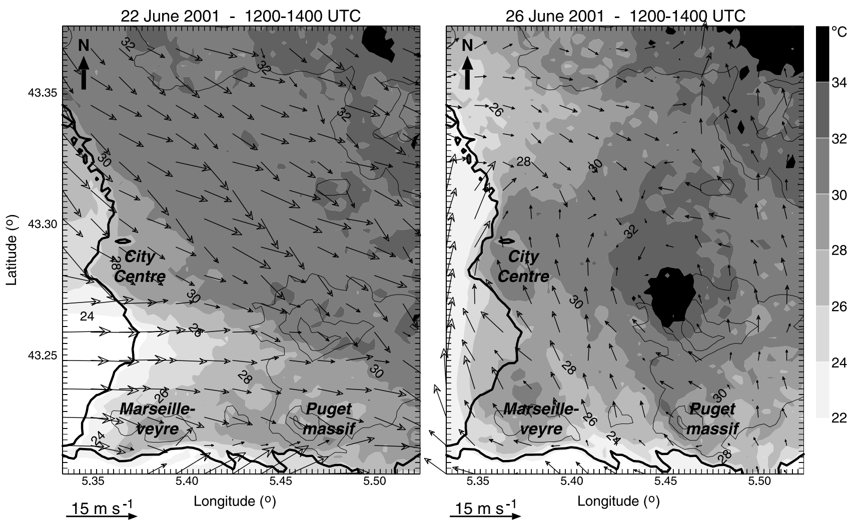

Fig. 5. 6-m potential temperature field integrated between 1200 and 1400 UTC for the 22 and the 26 June 2001, simulated by the model

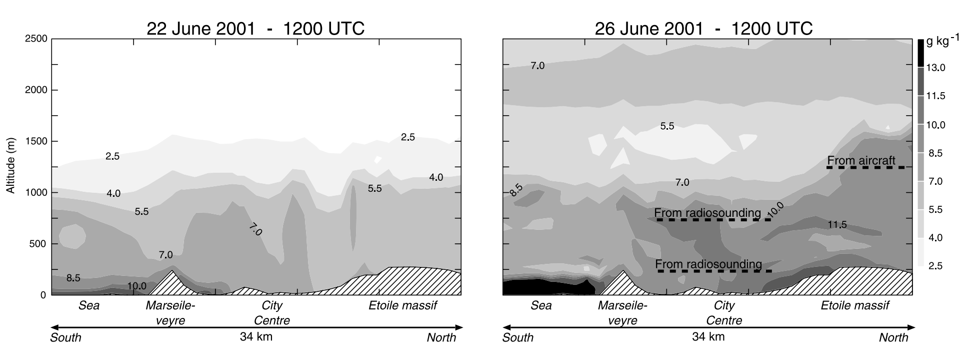

Fig. 6. North–south vertical section of modeled water vapor mixing ratio across Marseille, for the 22 and the 26 June 2001 at 1200 UTC. For the 26 June, the ABL top as well as the near surface cold and humid maritime air layer, estimated from aircraft and radiosounding measurements, are also labeled on the figure

To the north of Marseille, the height of the boundary layer is very comparable (not shown), what differs of the situation of the 26 June.

During the IOP 2b, the daytime temperature and humidity patterns are very different than for the 22 June (see the observed field on

Fig. 4b and the simulation on Fig. 5b). According to the modeled wind field near the surface, Marseille is under influence of local flows, which induce complex mechanisms over the city. It indicates that the flow arrives from the east, along the coastline. It enters inside Marseille, by passing through Luminy between the Marseilleveyre and Puget massifs, and brings cold and humid air masses. On the one hand, the warm area, observed in the south-east of the city core, is associated to a convergence after the passage of the Puget massif. On the other hand, the Marseilleveyre massif diverts the flow toward the west. This air mass passes above the sea before coming back toward the city by the north-west (Fig. 5b). This process is at the origin of the entry of cold and humid air, observed on the 6-m air temperature field, above the north districts of Marseille. The vertical structure of the atmosphere is also different than the previous one. An instrumented aircraft flew over Marseille in the morning of the 26 June. The successive south–north transects, from the sea to the Etoile massif (to the north of Marseille), at varying altitudes, give the evolution of the ABL at noon. Moreover, Delbarre et al. (2005) used the radiosounding, lidar and UHF radar measurements to determined the UBL height over the city at the same time. Firstly, the ABL is higher in the north of the Etoile massif (more than 1000 m) than over Marseille. Note that usually, the ABL is higher above the cities than above the countryside, because the vertical development of the UBL during daytime is favored by the turbulence induced by the characteristics of the urban canopy. Secondly, two successive layers are underscored above the city. The lowest one in the first 250 m, when the second one reaches about 750 m. The simulated vertical section of mixing ratio, plotted according to the same transect than the aircraft flight (Fig. 6b), indicates the same evolutions of the ABL. The two internal layers above Marseille correspond to the two maritime entrances in the south and the north of Marseille connected to the topographic effects mentioned previously (Fig. 5b). Above the city core, the UBL is much lower than for the 22 June (750 to 800 m instead 1250 m previously) because the south-east flow, which is installed since the morning, limits the warming of the atmosphere and the development of the UBL.

6. Conclusion

The regional and urban-scale simulations, conducted with the Meso-NH atmospheric model and the TEB urban parameterization, correctly model the meteorological situations observed during the second IOP of the ESCOMPTE-UBL campaign. This study underscores the quality of the 250-m resolution thermodynamic fields produced by the model at daytime. Although they strongly vary according to the IOP, the fine structure of the temperature fields above the Marseille area is well simulated. The meteorological and physical interpretation of these complex and varying organizations, as well as the evolution of the structure of the UBL, require the use of high resolution models. The simulation allows to analyze and understand the local mechanisms at the origin of these processes. The model outputs show that the parameters near the surface are largely influenced by the wind, especially by the sea breezes, which can be coupled to topographic effects, giving that the local relief is complex. In such situations, the warming of the atmosphere is limited, and the development of the Urban Boundary Layer is weaker than under synoptic and regional flow coming from land.

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