Atmospheric boundary layer characteristics during high ozone concentrations in the Rijeka Bay area

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Abstract
In this study, a time series from the ground level ozone monitoring station for Rijeka (Croatia) as well as the associated meteorological conditions were investigated. In the summer, during 13 to 19 August 2000, the afternoon hourly ozone measurements were consistently higher than the 180 μg m^{-3} which represents an information threshold of pollutant concentrations according to the national standards. During the night the ozone concentrations were unusually very high as well, above 100 μg m^{-3}. An analysis of the observations was performed to identify characteristics of the low-level wind in the Rijeka Bay and the results of a nonhydrostatic mesoscale meteorological model WRF were compared with the observations with respect to these characteristics. The contribution of the distant pollution sources to observed concentrations was evaluated by the atmospheric chemical model EMEP.

Keywords: ozone; sea/land breeze; slope winds; north-eastern Adriatic.

1. INTRODUCTION

During the last decades, many papers have been studied the high ozone concentrations as well as the severe photochemical pollution in Mediterranean area [1,2,3,4]. The north-eastern (NE) Adriatic, as the part of Mediterranean, is characterized by the high level of year–round solar radiation during warm part of the year. The ground level ozone (as a secondary pollutant) is particularly high during summer periods when intense solar heating enhances the photochemical activity and when the sea breeze circulation contributes to the (re)distribution of the pollutants.

The NE Adriatic, located in the western part of Croatia (Figure 1a) has very complex coastline. The area is characterized by the large Istria peninsula, the Kvarner Bay, and with the proximity of the mountain ranges parallel to the coast (Učka, Risnjak, Velika Kapela, Velebit). In the Kvarner Bay, several islands, where Cres and Krk as the biggest, and Rijeka Bay faces the Rijeka urban area. Rijeka is the main industrial town in the coast of Rijeka Bay. It is placed at the steep slopes of Risnjak mountain. During a warm season, a weak large-scale pressure gradient allows forming of the local thermal circulation in 50 % of all summer days along NE Adriatic coast [4]. Recent studies showed the formation of several small-scale phenomena e.g. the mesoscale eddies inside the Rijeka Bay and convergence zones above Istria and the island of Krk mostly as the result of the sea/land breeze (SLB) development [5,6,7]. The sea pass between Istria and island of Cres significantly canalized surface wind contributing to the formation of the anticyclonic daytime mesoscale eddy within the Rijeka Bay. On the contrary, the night-time cyclonic eddy developed there due to katabatic flow from the surrounding mountains. According to the numerical and climatological thermal circulation studies [5,6,7], the Rijeka Bay and especially Rijeka city is characterized by the low wind speeds. Because of the unique geographical surrounding of the Rijeka Bay, airborne pollutants are not easily ventilated out of Bay under light-wind conditions.

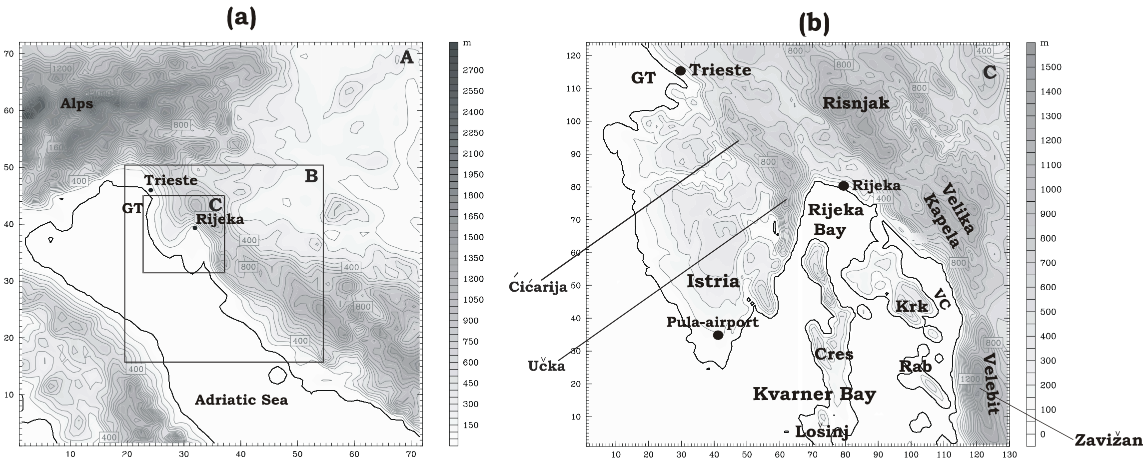

Figure 1. (a) Coverage of the nested WRF grids over the study area on the NE Adriatic coast. Frames indicate the coarse (A), medium (B) and the fine grid (C) model domains, respectively. Pula-airport measuring site is located at the tip of Istria peninsula. Rijeka is placed at the NE coast of the Rijeka Bay at the foot of Risnjak Mountain. The abbreviation GT means the Gulf of Trieste.

Rijeka is the only site that has the continuous ozone monitoring in the Rijeka Bay started from 1999 [3]. Despite of a declining trend of ozone in the Rijeka Bay Area from 1999-2007, the ozone levels were significantly high during 13 to 19 August 2000 (Figure 2). Then afternoon hourly ozone measurements exceeded consistently an information threshold of pollutant concentrations (180 μg m^{-3}) according to the national standards affecting a human respiratory system. During the nighttime, the ozone concentrations were unusually very high as well, above 100 μg m^{-3}. Therefore, the aim here was to detect the cause of these unusual ozone levels mentioned above by the available measurements and by models.

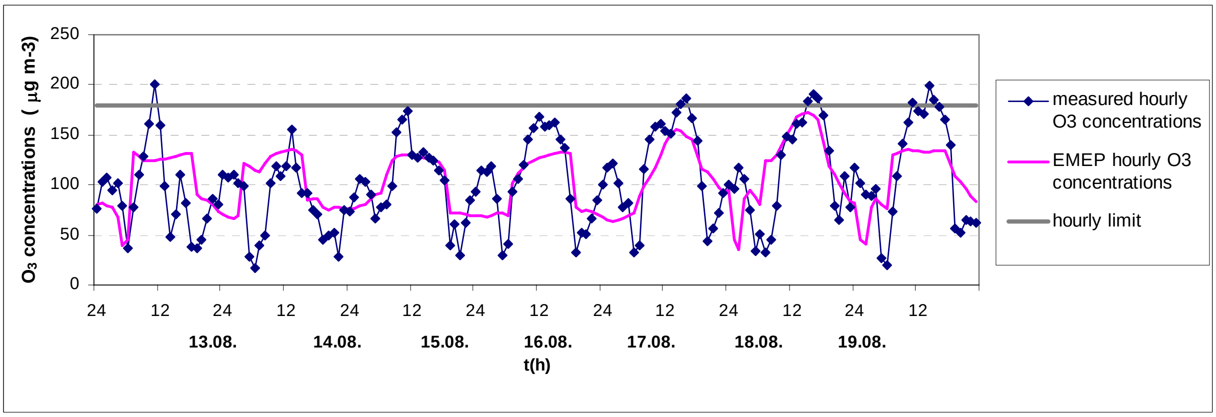

Figure 2. The hourly measured (diamonds) O_3 concentrations measured at Rijeka (lat =45°19'54"N: long =14°25'32"E, height=20 m a.s.l.)as well as EMEP hourly (solid pink line) from 13 to 19 August 2000.

2. STUDY PERIOD AND AVAILABLE MEASUREMENTS

2.1 Meteorological conditions during the case

Surface diagnostic charts and meteorological data from two meteorological stations in the NE Adriatic region were used in order to highlight the relevant surface wind characteristics. At the beginning of the period (12 to 19 August 2000), a ridge over the Azores' anticyclone reached NE Adriatic forming there almost no-gradient surface pressure conditions and a fair undisturbed weather (not shown). The surface wind data shows the SLB patterns over the Pula-airport and Rijeka (Figure 3). During 14-15 August, the surface anticyclone still existed over southern and western Europe but the shallow cold front crossed over the Eastern Alps south-eastward and was followed by a cold air outbreak (not shown). This shallow outbreak was observed in the continental part of Croatia. It latter produced a very light bora wind along the NE Adriatic coast, first in Pula-airport and afterwards in Rijeka (Figure 3). From 16 August, the synoptic situation was characterized once again by a ridge of high pressure over the southern Europe. The surface pressure gradient became weak, leading to light large-scale winds, which favoured again the development of thermal circulations and high ozone levels. Despite, the sporadic and weak bora occurrence, in general, the most of the days were characterized by the 24-hour periodical near-surface wind exchange in the target area.

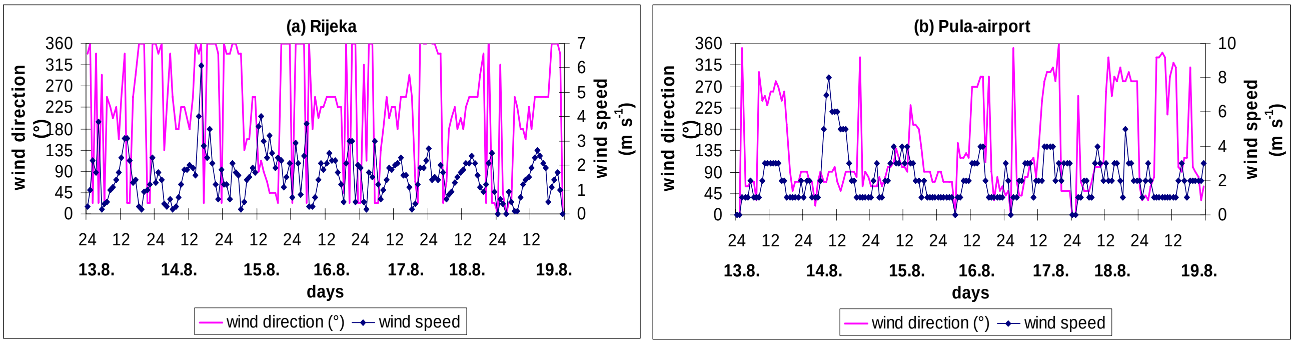

Figure 3. Horizontal wind speed (solid line) and direction (diamonds) from surface meteorological stations during high O_3 concentrations from 13 to 19 August 2000 at (a) Rijeka and (b) Pula-airport.

2.2 Ozone levels during the episode

The ground air quality station in Rijeka is placed in the urban area at the coast. It was influenced by the SSW thermal onshore flow (Figure 3a), except for 14-15 August, when light bora was diluted the atmosphere. According to the synoptic situation, the overall high ozone levels may be classified within two regimes: till and after 16 August 2000 (Figure 2). The hourly ozone concentrations in the second period were somewhat higher than those measured earlier. Still, the diurnal cycle of ozone represent typical observations for the polluted atmosphere [4]. The ozone accumulation starts around noon, lasts until 19 LST with the smallest concentrations around sunset and sunrise. The limit hourly value was exceeded mostly in the second part in the afternoon (usually from 14 to 16 LST) when the sea breeze was well established.

3. MODELS

3.1 WRF model

We used Weather and Research Forecasting (WRF) model [8]. The model employed a two-way nested configuration featuring a coarse domain with a 9-km; 3-km and 1-km grid spacing (on the Lambert conformal projection), respectively (Figure 1). For the two inner domains, we used a topography and land-use data base with 30’’ resolution. WRF dynamic and physical options used for the simulation are for all domains: an ARW dynamical core; a Mellor-Yamada-Janjic scheme for the planetary boundary layer; a rapid radiative transfer model for the longwave radiation and a Dudhia scheme for shortwave radiation; a single-moment 3-class microphysics scheme with ice and snow processes; the Eta surface layer scheme based on Monin-Obukhov theory and a five-layer thermal diffusion scheme for the soil temperature. On the coarse 9-km domain, the Betts-Miller-Janjic cumulus parameterization was applied, but without parameterization in the inner domains. Sixty-five terrain-following hydrostatic pressure coordinate levels were used with the top at 20 km. Initial and boundary conditions were updated every six hours with analyzed data from the European Centre for Medium-Range Weather Forecasts (ECMWF) at a 0.25° x 0.25° resolution.

3.1 EMEP model

The hourly regional O_3 concentrations have been calculated with the Unified EMEP model documented in [9]. The model simulates the long-range transport and deposition of air pollutants at a daily scale. The EMEP domain covers Europe and the Atlantic Ocean, with a horizontal resolution of 50 km and with 20 terrain-following layers in vertical up to 100 hPa. The meteorological input was obtained for every 3 hours, by the PARallel Limited Area Model with Polar Stereographic map projection (PARLAM-PS), a version for EMEP of the HIgh Resolution Limited Area Model (HIRLAM) a numerical weather prediction model.

4. RESULTS AND DISCUSSION

4.1 The WRF model results

WRF simulation was performed for the period characterized by maxima hourly ozone concentrations above 180 µg m^{-3}, namely, from 16 August 2000 at 12 UTC to 19 August 2000 at 24 UTC. Figure 4 shows a comparison of model results with available surface observations. The model in general simulated the wind directions quite well, while the wind speed is sometimes overestimated. It also reproduced the observed SLB pattern. Although, model underestimated the 2-m air temperature (Figure 4c), the agreement between measured and modelled values is still visible.

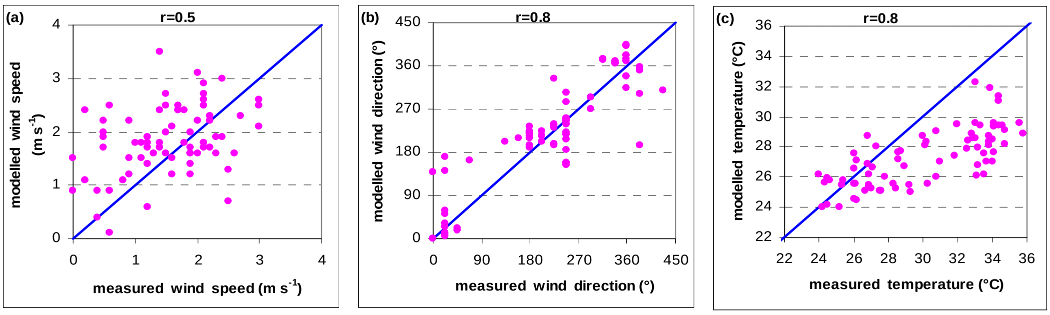

Figure 4. The modelled versus measured hourly averaged surface (a) wind speed, (b) wind direction and (c) temperature above Rijeka from 16 August 2000 at noon to 19 August 2000 midnight. In order to show exact discrepancies between the measured and modelled directions, wind directions spanning a range of 0-90º are sometimes enlarged by 360º.

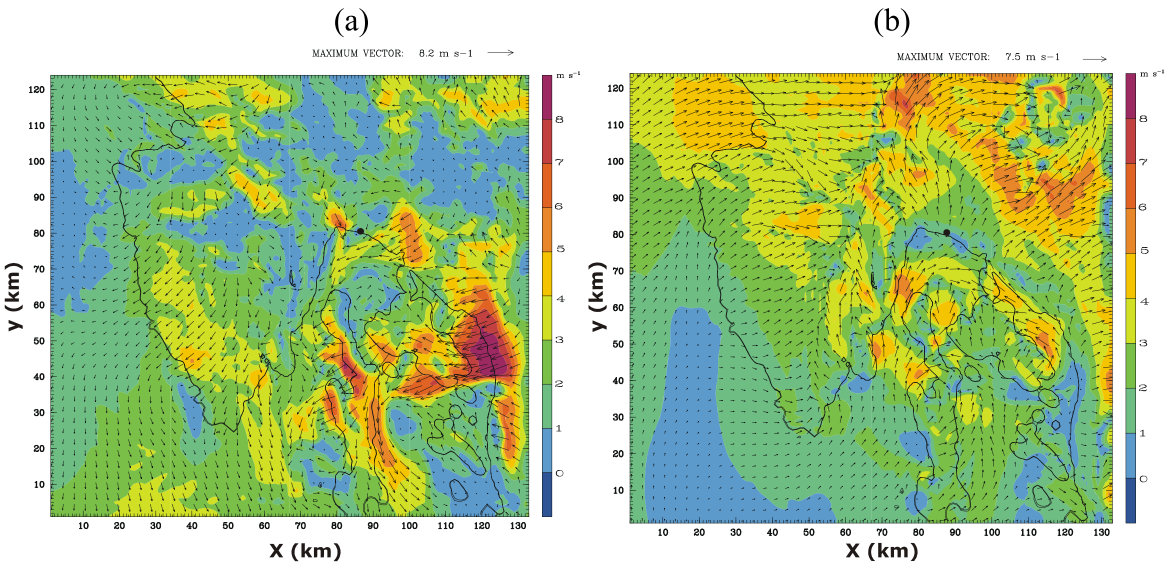

Figure 5. Development of the land/sea breeze can be seen by the near-surface wind speed (colour scale) and velocity (vectors) at (a) 06 LST and (b) 16 LST in the 1-km model domain. Black dot represents the position of Rijeka.

The wind field patterns from 17 and 19 August 2000 were quite similar. Therefore we made an arbitrary decision to focus on 17 August 2000 analyzing wind field at 06 LST (Figure 5a) and at 16 LST (Figure 5b). During the nighttime, in Figure 5a, the land breeze was blowing over most of Istria. The anticlockwise eddy appeared in Rijeka Bay similar as in [6]. The offshore winds above the coastal mountains (as a superposition of the land and downslope winds) were determined by the known mountain gaps: the first primary stronger flow between Velika Kapela and Velebit and the second weaker one near Rijeka. The stronger flow stretched to the islands of Cres and Lošinj. As shown in Figure 5b, during the daytime, over Istria, wind vectors suggest an interaction of two sea breeze systems which compete over the peninsula due to the convex coastline. This interaction between western and eastern sea breeze circulations is visible trough the convergence zone there. Mesoscale clockwise eddy occurred within Rijeka Bay with the channelling of the wind between Istria and the island of Cres as well as between mainland and the island of Krk that agrees with [6].

4.2 The EMEP model results

According to Figure 3, the observed hourly concentration of O_3 were satisfactory reproduced by EMEP model showing relatively high early afternoon ozone values during examined period. As shown by Figure 6, the horizontal ozone distributions revealed the ozone maxima in the NE Adriatic within Gulf of Trieste on 13 and 18 August that agrees with [4]. During weak bora event, this area had smaller concentrations (Figure 6b).

(a) (b) (c)

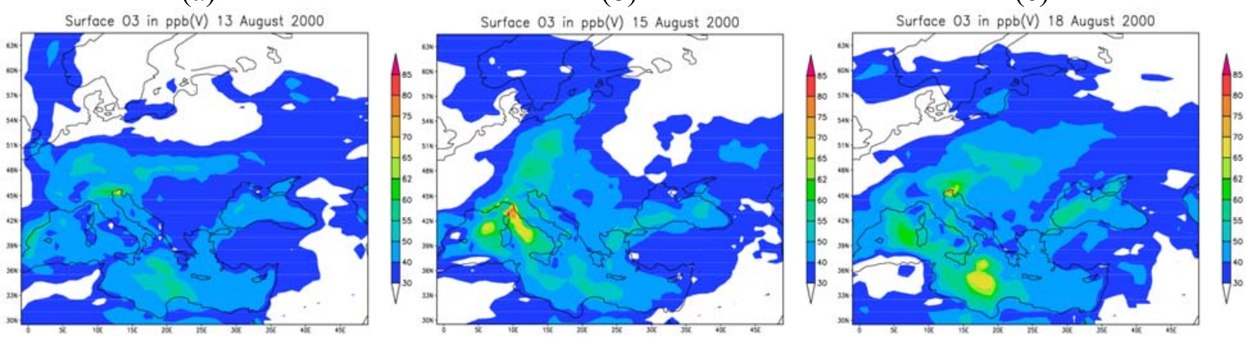

Figure 6. The horizontal distribution of daily mean surface EMEP O_3 concentrations (ppb) on (a) 13 August, (b) 15 August and (c) 18 August 2000.

4.3 The WRF trajectories

Figure 6 showed that an origin of ozone rich air masses were over the northern Adriatic Sea and its coastal regions. According to 48-hours trajectories in Figure 7, in general, the ozone originated from Gulf of Trieste was carried by the western sea breeze and then was caught by the convergence zone above Istria. During the nighttime, it was transported by the land breeze eastward over the sea, parallel to the Istria peninsula. The canalized thermal daytime flow through the sea pass carried the ozone (trapped inside shallow marine boundary layer) horizontally to the Rijeka Bay. Ozone that was northward from convergence zone over Istria, was transported through the valley between Ćićarija and Risnjak toward Rijeka.

5. CONCLUSIONS

We found that relatively very high ozone concentrations predominately originated from the boundary layer. It seems that the sources within the Gulf of Trieste contributed substantially to elevated ozone levels in Rijeka. This transport of polluted air was achieved by the thermal circulation regimes and consequent convergence zone over the Istria peninsula and canalized flow between Istria and the nearby island.

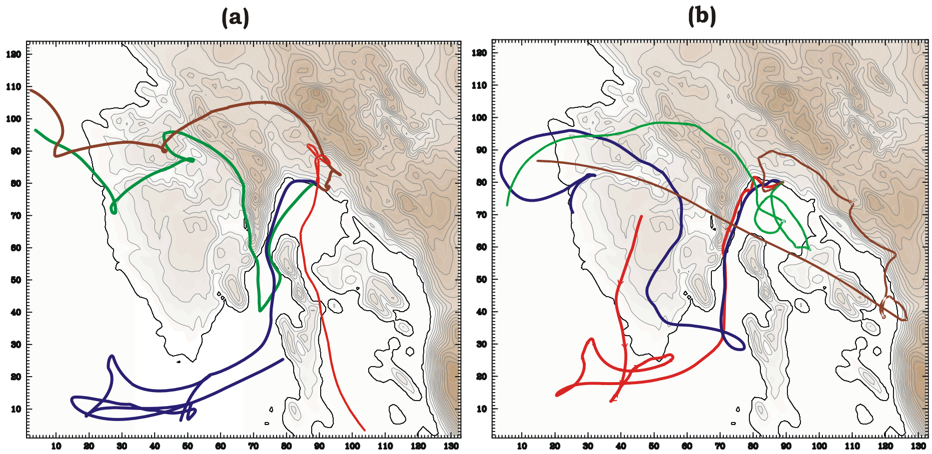

Figure 7. (a) 2-day backward 1000 hPa trajectories arriving at Rijeka every six hours (02 LST (red), 08 LST (brown), 14 LST (green) and 20 LST (blue)) starting from (a) 18 August 2000 and continue on (b) 19 August 2000. Parcel positions are given for every second hour for the wind field in the 1-km WRF domain.

Acknowledgements

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