NUMERICAL MESOSCALE SIMULATION OF ATMOSPHERIC CONDITIONS DURING SEVERE SO_2 EPISODE IN RIJEKA, CROATIA

M. Telišman Prtenjak[1], T. Nitis[2], Z. Bencetić Klaić[1]
[1]Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science, University of Zagreb, Croatia
[2]Laboratory of Geoinformatics and Environmental Application, Department of Marine Sciences, University of the Aegean, 81100 Mytilene, Greece

Abstract

A severe pollution episode occurred in Rijeka, Croatia during 3-5 February 2002, where a daily mean SO_2 concentration reached even 225.5 μg m^{-3}. A previous study of the above episode suggested the fumigation due to the weak synoptic circulation and high-pressure conditions.

Rijeka is a coastal industrial town surrounded by mountains, located at the Northern Adriatic, at a position where the sea has made its deepest incision into the European continent. Thus, it exibits very complex wind regime, which can affect the air quality. The aim of this study is to investigate mesoscale atmospheric conditions, and particularly airflow and turbulence within the lower troposphere during above severe pollution episode. The results were produced using 3-D, higher-order turbulence closure model and will help in the future rational design of integrated emissions control strategies for the greater Rijeka area.

Keywords: pollution episode, Sea Breeze, Numerical Model, North-Eastern Adriatic, Greater Rijeka area

1. Introduction

Rijeka is a coastal industrial town. In the Greater Rijeka Area (GRA), southeast of the city of Rijeka, some of the major individual sources of SO_2 in Croatia are found, such as thermal power plant and the oil rafinery. Namely, according to the Ministry of Environmental Protection, Physical Planning and Construction of the Republic of Croatia, http://www.mzopu.hr, main individual sources of SO_2 in the GRA are the oil refinery and thermo power plant. These two, according to the above mentioned source, emitted during the 2002 about 20 % of the total estimated Croatian emissions of SO_2, where 8933 and 4909 tones of SO_2 correspond to the oil refinery and thermo-power plant, respectively.

Facing the Adriatic Sea and surrounded by mountains, Rijeka is frequently under the influence of thermally induced circulations. In this coastal environment, a region of the very complex wind regime exists, where an interaction among small-scale circulations, such as sea/land breezes, urban heat island circulation and mountain/valley winds occurs. The local circulations can superpose and produce higher pollution in this complex area because the pollutants from sources located in coastal areas sometimes recirculate (Robinsohn *et al.*, 1992) and add to the newly emitted ones.

Results of many studies (e.g. Robinsohn *et al.*, 1992; Soler *et al.*, 2004; Tayanc and Bercin, 2007) showed that the severe air-pollution episodes around the world are very often connected with the high-pressure condition and weak winds. Recently, a human health risk situation occurred in Rijeka where during 3 to 5 February 2002, a daily mean concentration of SO_2 reached even 225.5 μg m^{-3}. According to Jeričević *et al.* (2004) this episode caused by fumigation was the result of the weak synoptic circulation and high-pressure conditions. Additionally, management of the major SO_2 sources in the GRA claimed that their emissions during the episode were not higher than usually.

The aim of this study is to evaluate the winter mesoscale atmospheric conditions, and particularly airflow and turbulence within the lower troposphere during the above episode. For this purpose, the nonhydrostatic mesoscale meteorological model MEMO was used to simulate and analyse the local circulation phenomena over the GRA. MEMO belongs to the European Zooming Model (EZM) system, a comprehensive model system for simulations of wind flow and pollutant transport and transformation (Moussiopoulos, 1995). The model has been previously validated against an extensive data set such as for Athens (Kunz and

Moussiopoulos, 1995), Barcelona (Soriano *et al.*, 2001), Zagreb (Klaić and Nitis, 2001-2002; Klaić *et al.*, 2002) or Rijeka (Nitis *et al.*, 2005; Prtenjak *et al.*, 2006).

2. Study area and model configuration

The GRA is located in the western part of Croatia (Fig. 1(a)) and is characterized by complex topography. It is a mountainous area open to the sea towards the south, where several islands are located; Cres and Krk are the biggest ones (Fig. 1(b)). The Rijeka urban area faces Kvarner bay, with rather high mountains (more than 1250m above mean sea level (amsl) and steep slopes along its eastern coastline. Westwards from Rijeka, the terrain rises very abruptly along the coastline, forming a physical boundary between the Istria peninsula and Kvarner bay. A more gradual rise of the terrain is found north-west of the Rijeka urban area, with an elevation of less than 500 m amsl, where a roughly triangular valley extends towards the Gulf of Trieste, which is near to the north-western boundary of the study area.

A one-way nested system based on the expanded radiation boundary conditions was applied, in order to account for all relevant orographic influences on the flow field, while an extent of the horizontal domain which includes a reasonable portion of land and sea masses was defined. Coarse-grid simulations covered an area of 300 km × 300 km with a 3 km horizontal grid spacing (outer frame in Fig. 1(a)), while the fine-grid simulations were performed within an area of 100 km × 100 km at a horizontal resolution of 1 km (inner frame in Fig. 1(a)). In the vertical, 25 layers were assumed allowing for finer resolution at lower altitudes; the thickness of the lowermost layer was 20 m. In order to better incorporate the larger-scale forcing, the model top was set at height H = 6000 m amsl. Meteorological input information, consisting of vertical profiles of wind speed, wind direction and temperature, was obtained from the Udine and Zagreb radiosonde stations.

The initialization of prognostic model MEMO has been designed to be performed with suitable diagnostic methods: a mass-consistent initial wind field is formulated using an objective analysis model. Scalar fields are initialized using appropriate interpolating techniques (Kunz and Moussiopoulos 1995). Data required to apply the diagnostic methods may be derived either from observations or from larger-scale simulations.

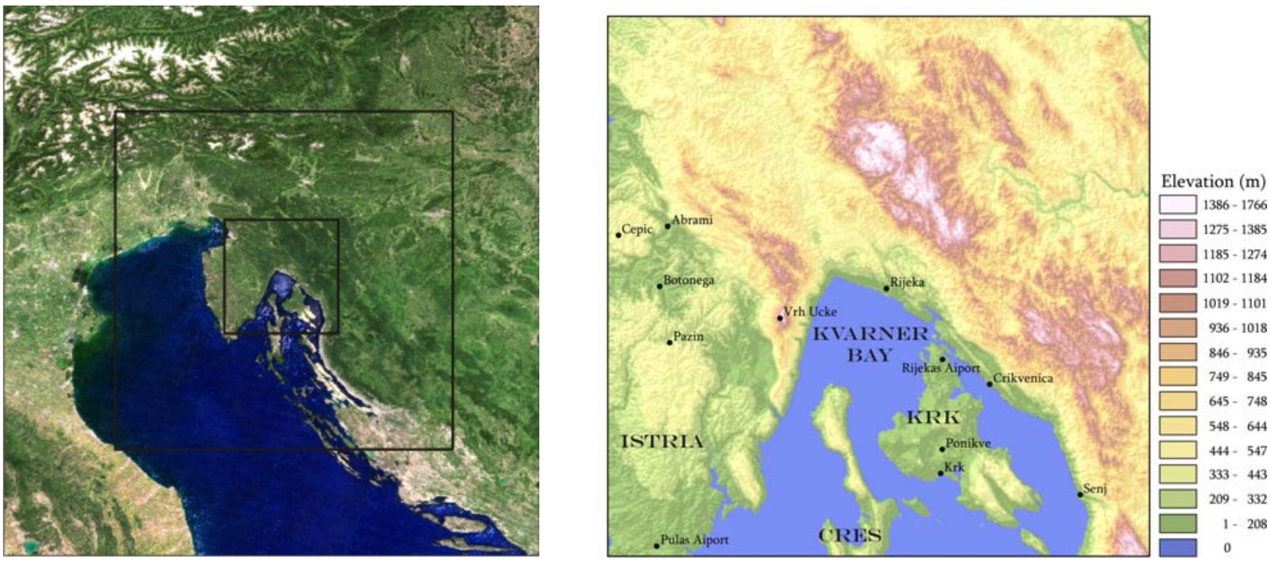

***Figure 1*:** (a) Configuration of nested grids over the study area on the Northern Adriatic Coast. Frames indicate the coarse-grid (outer frame) and the fine-grid (inner frame) model domains, respectively. (b) Anaglyph for the fine-grid domain. Positions of the routine measuring sites are also shown. Centres of both domains are in Rijeka 45.338°N, 14.430°E.

The upper-level meteorological charts over Europe for the period under study show a high pressure field over the central and southeastern part of Europe with weak pressure gradient over the northeastern Adriatic coast. The latter was accompanied by weak surface winds and stagnant conditions with fog and low stratified cloudiness. As of 5 February, the high pressure field started to weaken, indicating the change of the synoptic conditions due to Genoa Cyclone that approached the Kvarner Bay. Additionally, the radiosounding performed in Udine (situated in the coarse model domain; Fig. 1(a) revealed a high static stability ranging from 5.6 K km^{-1} on 2 February to 5.2 K km^{-1} on 5 February. During the whole examined period, the winds in the lowermost 2 km in Udine are mostly less than 4 m s^{-1}, and they vary from south-westerly to westerly.

3. Development of the input database

A detailed orography data set for the study area was derived from the Shuttle Radar Topography Mission (SRTM) database (Farr *et al.*, 2007). The latter is the most complete high-resolution digital topographic database of the Earth. It uses a horizontal grid of approximately 90 m and it was developed by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The land use data set originated from the Corine land cover 2000 (CLC 2000) database, which is part of the European Commission programme to COoRdinate INformation on the Environment (Corine), developed by the Topic Centre on Terrestrial Environment (ETC/TE). The CLC 2000 Land Cover database includes 44 land cover types with a horizontal resolution of about 100 m. Despite the fact that in MEMO applications the original 44 land use types are reclassified into 7 more general ones, in the present study, the requirement for a more accurate representation of the urban environment led to the use of 11 general land use types. A short description concerning the processing of MODIS satellite data for estimating the surface parameters, daytime Land, Sea Surface Temperature and albedo, is given below.

Initial daytime Land and Sea Surface Temperature (LST nad SST) over the study area were deduced from the Moderate-resolution Imaging Spectro-radiometer (MODIS) instruments aboard the NASA Terra and Aqua satellites observations (Wan et. al., 2002). The inputs consisted of daily LST and SST composites with spatial resolution of 1 and 4 km respectively. However, this procedure can lead to the inclusion of pixels within areas of cloud shadow. To reduce the presence of cloud shadows, the data were converted to 8-day composites.

Land surface albedo, i.e. the fraction of incident radiation reflected by a surface, controls the amount of short wave absorbed by the Earth's surface and thus is an important modulator of the surface energy budget. However, this parameter remains one of the largest radiative uncertainties associated to modelling attempts. Uncertainty occurs because of the fact that models commonly prescribe albedo using in situ observations, which rarely are sufficiently dense to characterize albedo at a regional scale accurately (Davidson and Wang, 2004; Nair *et al.*, 2005).

In the present study, the MODIS / Terra-Aqua albedo 16-day 1 km product was used for the aforementioned time periods (Fig. 3). Although a Terra-Aqua albedo product appears similar to a Terra only product, the data quality is much enhanced using the Terra-Aqua combination. This product provides both the white-sky and black-sky albedo (at local solar noon) for MODIS bands 1-7, as well as for three broad bands (0.3-0.7 μm, 0.7-5.0 μm and 0.3-5.0 μm). The latter albedo broad band was used, since the wavelengths 0.3-5.0 μm affect the surface energy balance (Wang *et al.*, 2004). White-sky albedo (α_{ws}) is defined as the albedo in the absence of a direct component when the diffuse component is isotropic and independent of the solar zenith angle. Black-sky albedo (α_{bs}) is defined as the albedo in the absence of a diffuse component and is a function of the solar zenith angle. These two components can be combined as a function of the diffuse skylight fraction (S) for a representation of an actual albedo (Lucht *et al.*, 2000):

$$\alpha(\theta,\Lambda) = (1- S)\,\alpha_{bs}(\theta,\Lambda) + S\alpha_{ws}(\theta,\Lambda) \qquad (1)$$

where θ is the solar zenith angle and Λ is the wave band of $\Delta\lambda$ width (with λ being the wavelength).

However, diffuse skylight fraction (S) is not readily available and as a result Eq. (1) cannot be used directly. The α_{bs} was used in the present study since it should be relatively close to the actual albedo as it represents the integration of the α_{bs} over all solar zenith angles (Wang *et al.*, 2004).

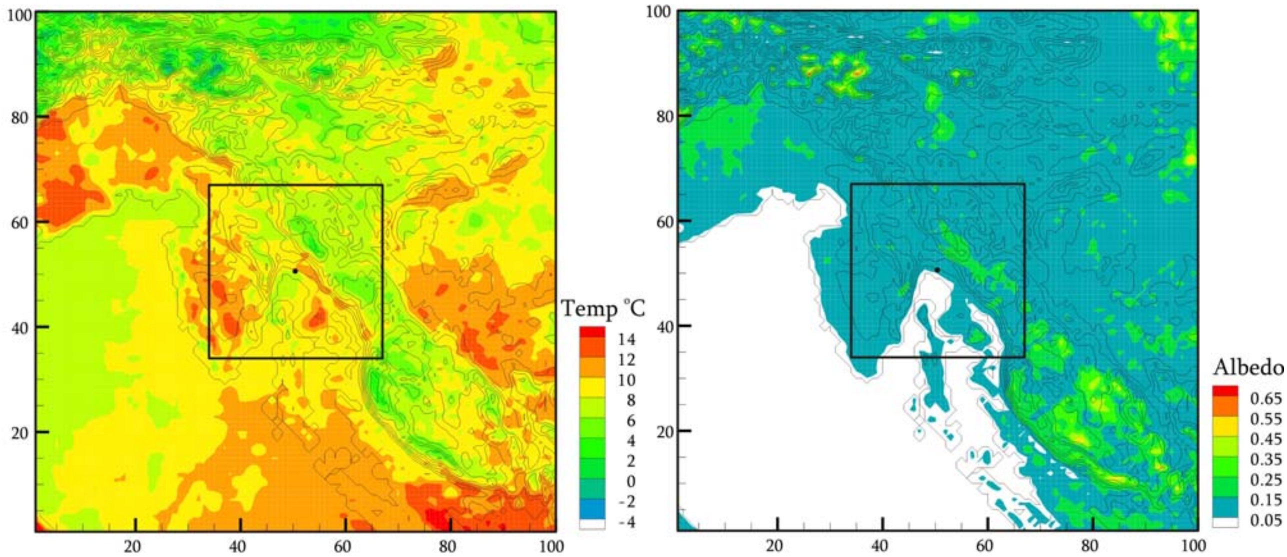

Figure 2**:** Surface temperature (left) and albedo (right) for the area under study for both coarse (outer) and fine (inner) model grid domains for (a) 3-5 February 2002. Topography contours are given every 200 m between 0 and ~2600m, whereas bullet indicates the centre of both numerical grids. Values for the land and sea surface temperature originated from MODIS Terra sensor on contrary for the albedo values from MODIS / Terra-Aqua albedo 16-day 500 m product was used.

4. Results

According to Jeričević *et al.* (2004), the daily concentration of SO_2 started to increase considerably on 3 February 2002. Compared to the previous day, the daily concentration approximately increased 300%. On 2 February, that was characterized by sunny conditions and a land-sea temperature difference greater than 10 °C, the daytime boundary layer reached the stable polluted layer. Jeričević *et al.* (2004) argued that observed SO_2 concentration growth on 3 February was due to pollutant entrainment into the boundary layer. The maximum concentration occurred on the 4th. Therefore, we concentrate our analyses on the wind field during suggested fumigation process strengthening i.e. on the 3 and 4 February 2002.

4.1 The model verification

During anticyclonic periods, the model comparison with the measurement showed the satisfactory model ability to simulate mesoscale phenomena (e.g. Klaić, and Nitis, 2001-2002; Klaić *et al.*, 2002; Nitis *et al.*, 2005; Prtenjak *et al.*, 2006). In order to validate the simulation results, we compared them with the available surface observations furnished by automatic meteorological and climatological stations in the inner domain (Fig. 1). As seen from the Fig. 3, for some sites the modelled and measured wind vectors agree reasonably well, while for other sites (e.g. in central Istria) agreement is poor. The model rather frequently underestimated the wind speeds. Such result was expected since low wind speed is generally difficult to model (Mahrt and Vickers, 2006; Mahrt, 2007). Due to low wind speeds, the measured wind directions are highly variable while the modeled are more organized into local flows. Such result is expected since wind speed lower than 2 m s^{-1} is generally difficult to model. Additionally, the climatological stations provided only the strength of the wind (the Beaufort scale). Thus, converting the wind strength into the wind speed (m s^{-1}) represents another source of discrepancies between measurements and model.

In Rijeka (Fig. 4), the wind direction is reproduced reasonably well, although the wind speed overestimation appears. Still, knowing the overwhelmingly complex terrain, finite resolution of the model and its parameterizations the overall correspondence exists between the measurements and the model.

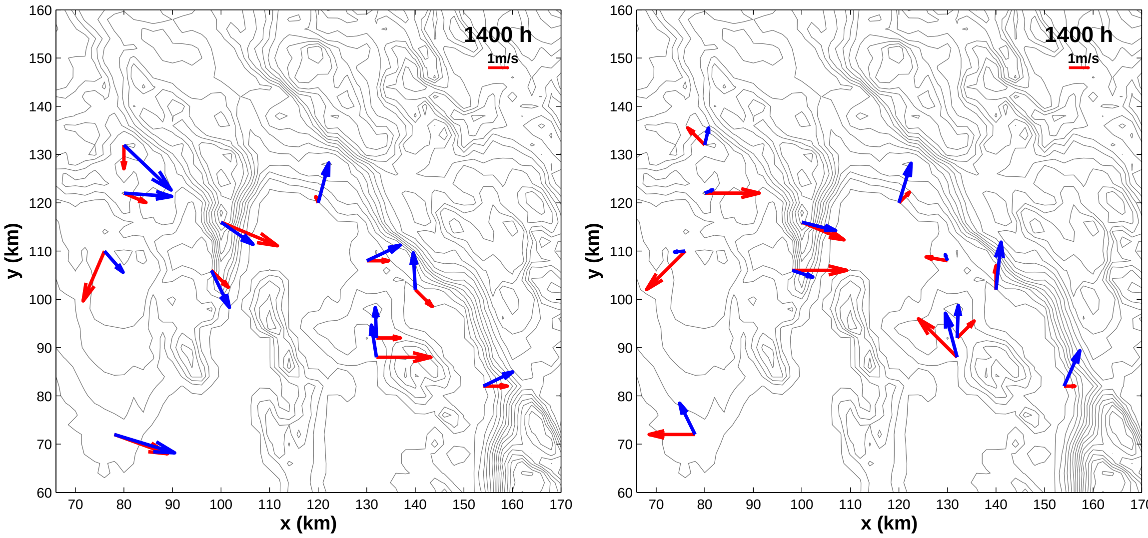

Figure 3**:** The 10-m wind from meteorological and climatological stations (red arrows) and model simulations (blue arrows) at 1400 hour on 3rd of February 2002 (left) and on 4th of February 2002 (right).

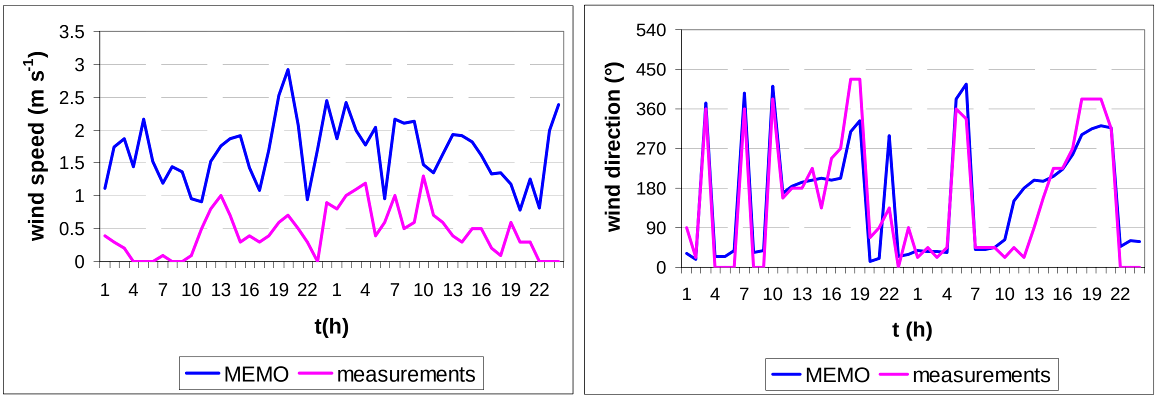

Figure 4**:** The wind speed (right) and wind direction (left) from measurements (pink) and model simulations (blue) in Rijeka during 3rd and 4th of February 2002.

4.2 The modeled wind field

On 3 February at 0700 h, over the Istria peninsula, weak southeasterly wind is present, while above the Učka mountain, the downslope winds are found. Within the Rijeka Bay, southeasterly wind meets the downslope wind from Risnjak leading to the formation of the anticlockwise rotation vortex. Such a formation in the wind field is already observed in the same area, during nighttime summertime anticyclonic conditions (Prtenjak *et al.*, 2006). In time, (2100 h), southeasterly winds above the Greater Rijeka Area and the northern part of island of Krk strengthen as well as eddy within the bay. During next day (Fig. 3), similar airflow pattern over Rijeka Bay remains.

On the 3rd of February at 0700 h, over the Istria peninsula weak southeasterly wind is present and above Učka mountain, the weak downslope winds can be observed. Within the Rijeka Bay the southeasterly wind meets the downslope wind from Risnjak leading to the formation of the very weak anticlockwise rotation vortex. Such a formation in the wind field is already observed in the same area, during nighttime summertime anticyclonic conditions (Prtenjak *et al.*, 2006). During the day (toward 2100 h) southeasterly winds above greater Rijeka area and northern part of island of Krk strengthen as well as the eddy within the bay. Istra is under influence of the weak northwesterly winds and the channeled flow forms between Istria and the island of Cres. Since the wind eddy is present above the major area of the Rijeka Bay, Rijeka is under significant influence of the southeasterly winds which transport the air from both, the northern part of the island of Krk and from the along-coast region southeast of Rijeka. It is important to note that both areas are important from the air quality point of view. Namely, at the northern part of the island of Krk, approximately 13 km southeast of Rijeka, a petrochemical industry is located. On the other hand, about 7 km southeast of Rijeka the industrial zone with among others, an oil refinery is placed. Thus, conditions shown in Fig. 5 are favourable for the transport of pollution from these two areas toward Rijeka.

On 4 February, when the maximum SO_2 concentration reached its maximum, the wind field show very similar characteristics as on the previous day (not shown). Thus, according to the model results, the conditions favourable for the transport of polluted air towards Rijeka continue. Additionally, weak winds presented in upstream areas result in the air-mass stagnation and air-pollutant accumulation.

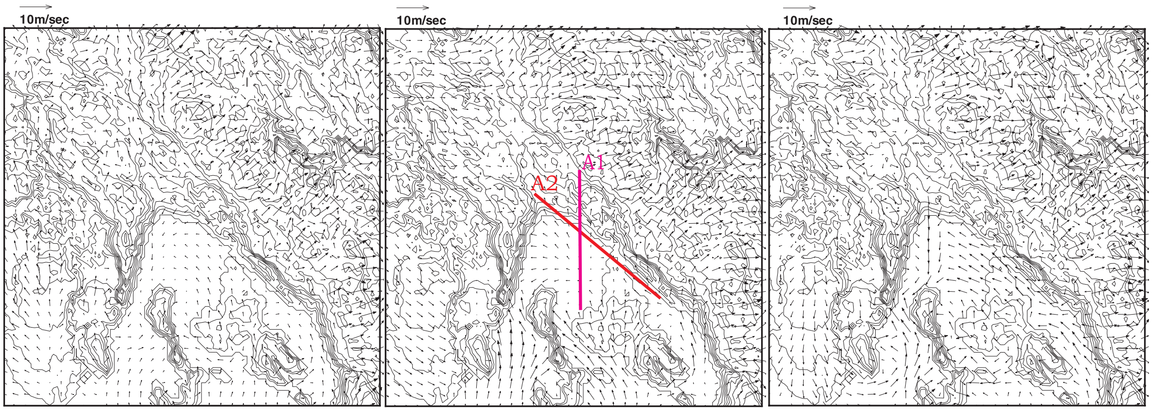

Figure 5: Predicted surface wind field at 10 m above ground level on 3rd of February 2002 at 0700 h (a), 1400 h (b) and 2100 (c). The wind vectors are given at a horizontal resolution of 3 km, with a reference vector near the upper right-hand corner. Lines A1 (pink) and A2 (red) show locations of the vertical cross-section.

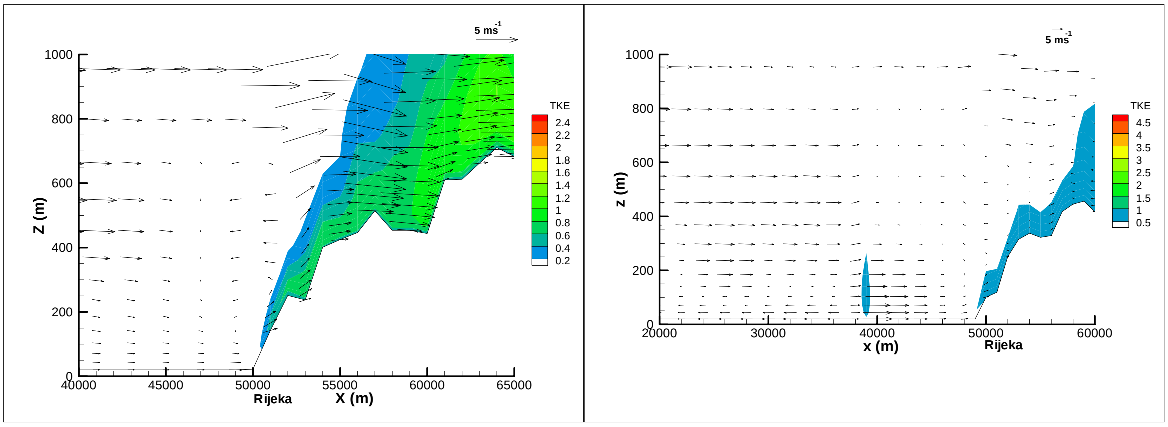

Figure 6: Vertical cross-sections of the modelled wind (ms^{-1}) and turbulent kinetic energy (m^2s^{-2}) above Rijeka on 4th of February 2002 at 1400 h: north-south section along A1 (left) and along the coast section A2 (right). The bases of the cross-sections A1 and A2 are shown in Fig. 5.

The above arguments are further supported by the vertical cross-sections (Fig. 6). These show dual processes which contribute to the maximum SO_2 concentration on 4 February. Firstly, the boundary layer is shallow, approximately 150 m (Fig. 6, left). Above it, a weak circulation can be observed which indicates that the pollutants are presumably drawn into the turbulent layer. In addition, in the region from 5 to 10 km south of Rijeka, air subsidence is found in the lowermost layer of about 800 m. Secondly, a prominent southeastern flow towards Rijeka (i.e. parallel to the coastline) is found in the first about 200 m of the troposphere (Fig. 6, right). According to the model results, the highest low-level wind speeds, up to about 7 m s^{-1}, are found in the region 6 – 10 km southeast of Rijeka, i.e. above the industrial zone. Between this region with the high low-level wind speeds and the town of Rijeka a flow stagnation is found, which favours the accumulation of polluted air. The region of stagnant winds stretches aloft up to about 700 - 800 m asl and it is slanted aloft towards southeast. Thus, conditions favourable for the accumulation of air are found in rather deep layer.

5. Conclusions

An attempt was made to examine the relationships between mesoscale circulation and high SO_2 concentrations recorded in the coastal town of Rijeka. The results demonstrated a successful multi-day simulation in the GRA and reasonably good agreement with the available observations. Further, model results suggest several facts that can be responsible for the occurrence of the severe pollution episode. These are as follows: 1) Transport of the air from regions with major pollution sources towards Rijeka, 2) Airflow stagnation region upstream of Rijeka that is favorable for pollutant accumulation and 3) air subsidence in the lowermost, approximately 800 deep layer south of Rijeka, which can further facilitate pollutant accumulation.

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