TOPOGRAPHIC FLOWS AT THE NORTH-EASTERN ADRIATIC COAST

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Abstract: A typical summertime anticyclonic situation over the north-eastern Adriatic coast is studied using a 3-D nonhydrostatic meso-γ-scale model. The aim is to evaluate small-scale variability in the thermally driven mesoscale circulations over very complex terrain. The simulations show a development of two diurnal mesoscale eddies inside the Kvarner Bay. The nighttime deeper ones exhibit anti-clockwise rotation, while the late afternoon shallow one shows the rotation in the opposite direction. Their appearance and dynamics are connected primarily to the coastline shape and topography. The convergence zones (CZs), as a result of the merged sea breezes, develop over Istria and the island of Krk. The intensity, speed and position of these CZs are examined. The results reveal that the CZ over the island of Krk is connected with a baroclinic low-level jet (LLJ). While the governing factor of the Istrian CZ is differential heating between Istria and the surrounding sea surface, the CZ over the island of Krk (and LLJ) is basically determined by the terrain and coastal geometry. The influence of the synoptic flow on the mentioned local characteristics is relatively small.

Keywords *– topographic flow, low level jet, sea/land breeze*

1. INTRODUCTION

Various wind regimes occur along the eastern Adriatic coast; e.g. a strong, cold and dry downslope wind called bura, a warm and moist sirocco and a sea land breeze (SLB). The local SLB along the Croatian coast has not been examined systematically, opposite to the reasonably well-examined and documented bura or sirocco winds (e. g. Brzović and Strelec Mahović 1999, Belušić and Klaić 2004). Several studies examined the SLB in a more qualitative than quantitative way representing the wind regime by wind roses or sketching. For some meteorological stations Orlić *et al.* (1988) analysed the average 24-hourly cycle of the surface wind vectors by rotary spectra analysis. A first attempt to improve the knowledge of the 3D wind field characteristics of this kind at the northeastern (NE) Adriatic was made by Nitis *et al.* (2005). A numerical model was applied for simulating the main characteristics of the SLB circulation for three meteorological periods which favour the development of the local circulation phenomena. However, there is no detailed systematic, 3D time-dependent study of small-scale variability in the wind field in this area. Therefore, the aim of this work is to analyse both the horizontal and vertical structures of the thermally driven and orographically modified flows in the presence of a complex coastline and numerous islands, under typical summertime conditions.

2. THE MODEL AND DESCRIPTION OF THE NUMERICAL EXPERIMENTS

Here, 3D nonhydrostatic numerical simulations by the MEso-γ-scale model, MEMO6 (e.g. Kunz and Moussiopoulos 1995) of a real, typical case are used. MEMO6 solves the continuity equation, the momentum equations and transport equations for scalars (such as pressure, humidity, potential temperature and turbulent kinetic energy) for the unsaturated planetary boundary layer (PBL). Model equations are expressed in a terrain – following coordinate system. The energy and water budget equations are solved at the air-soil interface to obtain the temperature and moisture at the surface. The model domains (Fig. 1) cover Istria and the Kvarner bay with ceter at Rijeka (φ= 45,33° N, λ = 14,45° E). Nested grid simulations were performed at horisontal resolution of 2 km for the coarse (240 x 240 km^2) and 1 km and fine (100 x 100 km^2) domains with the model top at 6000 m. The land-use data is taken from Global Land Cover Database as in Klaić *et al.* (2002). Seven land-use types were employed with the constant sea surface temperature of 20.5 °C. Since weather conditions favoring above circulations occur during the summertime anticyclone over Mediterranean, we selected one such period (19 – 20 June 2000). The 20 June 2000 was selected for an extensive analysis as distinct and regular quasi-periodic exchange from offshore to onshore flow was observed at chosen coastal stations; 1 = Opatija and 2 = Malinska (Fig. 1). The wind and temperature profiles from ALADIN/LACE model (ALADIN International Team 1997) were used as the model initial and boundary conditions. Apart from the simulation of the real land use (called control run), we performed two additional numerical tests (T1 and T2). The first test (T1) corresponds to the situation where the real synoptic conditions and the idealised topographies (the maximum height of the land surface is 10 m) are used; while the second (T2) describes idealised synoptic forcing (0 m s^{-1} wind profile and a linear Θ profile of 4 K km^{-1}) over the real topography.

3. RESULTS AND DISCUSSION

The surface wind distribution over the fine model domain on the 20th June (real case), at 10 m above ground level (AGL), is presented in Fig. 1. At 0200 h local time (Fig. 1a) the wind is weak over most of Istria (~ 2 m s^{-1}), while two cyclonic circulations in the wind field appear above the sea; one in the Rijeka Gulf and the other between Istria and the island of Cres. To study the bigger one in more details, the vertical vorticity component ($\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$) and the horisontal divergence ($D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$) are computed over the sea in a small arbitrary chosen sub-domain of ~ 20 x 20 km^2 (rectangle in the Fig. 1). The eddy structure in the Rijeka Gulf reaches its maximum positive ζ, 25 times higher than the value of Coriolis parameter at the beginning of its vigorous onset. It develops in a layer 600 m thick on the left side of the domain, which more or less, corresponds to the coastal marine PBL depth. The proceeding hours (until 0800 h) are roughly the eddy lifetimes during anti-clockwise rotation. In the afternoon, the eddy occurs again but in the opposite direction (Fig. 1b), culminating in the evening in a shallower layer (below 300 m). Its decay occurs during the night and is followed by the transition to the opposite sense of swirling. The divergence, D, which has generally smaller values than ζ, but still 15 to 20 times higher than the value of Coriolis parameter in the sub-domain, follows the “rotation” process.

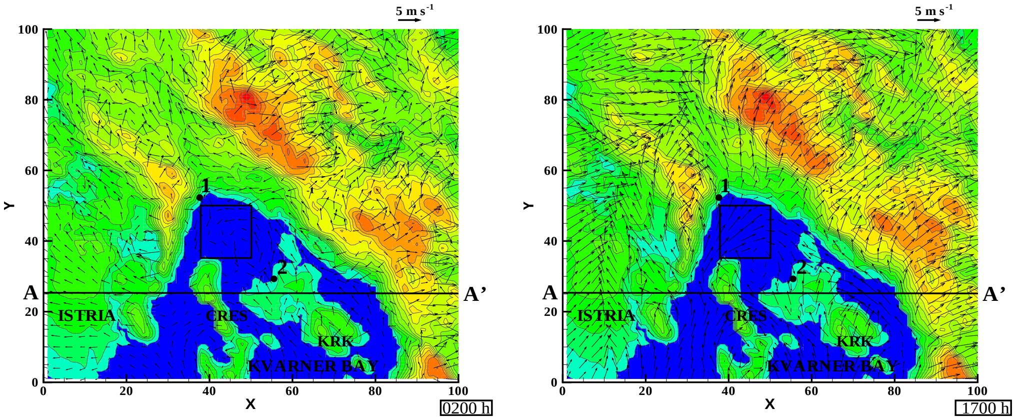

Figure 1. Map of Istria and Kvarner bay, showing the measuring sites (1 = Opatija, 2 = Malinska) and the fine (100 x 100 km^2) model domain. The wind vectors, that are given with a horisontal resolution of 3 km, show the surface wind fields 10 m AGL for the control run for 0200 h (left) and 1700 h (right) on the 20 June 2000.

During the morning, two sea breeze (SB) cells start to develop and to penetrate inland; one of the cells at the Opatija and Rijeka stations while the other over the southern and south-eastern region of Istria. Another SB cell is formed especially over the southern part of the island of Krk. The inland western SB penetration producing with the southern and southeastern SBs an updraft in the strong convergence zone (CZ). During the afternoon, as the western SB becomes stronger (maximum speeds are around 6 m s^{-1} in the onshore layer of 1000 m in the PBL) than in the late morning hours, the Istrian CZ moves eastward (Fig. 1b). The Istrian CZ lasts until the stabilization processes in the coastal environment overcome the daytime differential heating. Similar to the Istrian CZ, the additional near-surface CZ is generated over the NE part of the island of Krk owing to topographical thermal forcing and channelling. Since the island of Krk is still a relatively small landmass, the merging of the SB is already around 1100 h, consistent with results of Xian and Pielke (1991). The final merged SB moves toward the channel between the island of Krk and the mainland (Fig. 1b). During the day, the channelling effect between the mainland and NE part of the island of Krk is likely to enhance the stronger CZ over the NE section of the island, contributing to the stronger and more consistent SB monitored in this side of island. This CZ is connected with the formation of a coastal baroclinic low level jet (LLJ) below 200 m after 1400 h (Fig. 1b). The acceleration of the wind with significant vertical wind shear starts under conditions of fully developed convective mixing inside the CZ. Such type of the jet is found at the other locations too, such as for the Baltic coast (e.g. Tjernström and Grisogono, 1996) or at the Mediterranean coast of southeastern Spain (Kottmeier *et al*., 2000). After the coastal LLJ has weakened sufficiently (after 2000 h), the CZ propagates over the sea.

Figure 2 demonstrates the model's ability to simulate the onshore and offshore flows typical for the SLB in Opatija and Malinska. Despite the fact that the model underestimated the wind speed at Opatija from 1300 to 1800 h, the overall agreement between the measured and modelled wind was still satisfactory (Fig. 2a). Such temporary discrepancy could be expected since the model refers to the average value over an area of 1 km^2 stretched around 10 m AGL, while the local measurements were taken at a point 15 m AGL. The wind direction was reproduced very well (Fig. 2b). The ability of the model to simulate the SLB at Malinska is satisfactory (Figs. 2c,d), although a nocturnal wind speed overestimation appears; however, this is expected since wind speeds lower than 2 m s^{-1} are generally difficult to model. At such low wind speeds the observed flow is generally very variable, whereas the modelled wind is more organised into offshore flows.

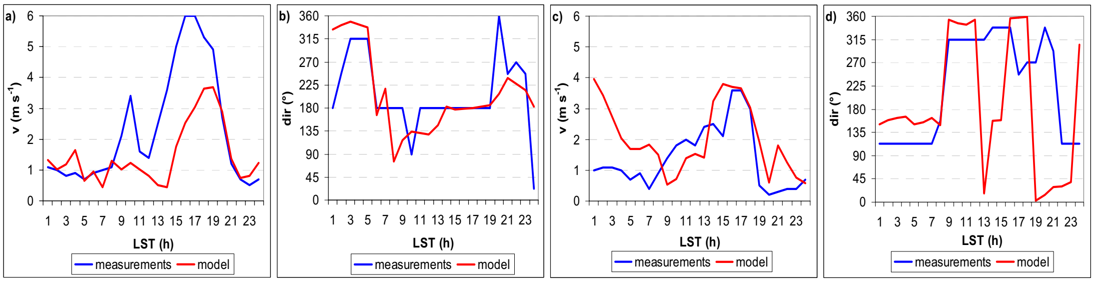

Figure 2. The average surface wind speeds and wind directions (blue lines) versus modelled at 10 m AGL (red lines) for Opatija (a,b) and Malinska (c,d) for 20 June 2000.

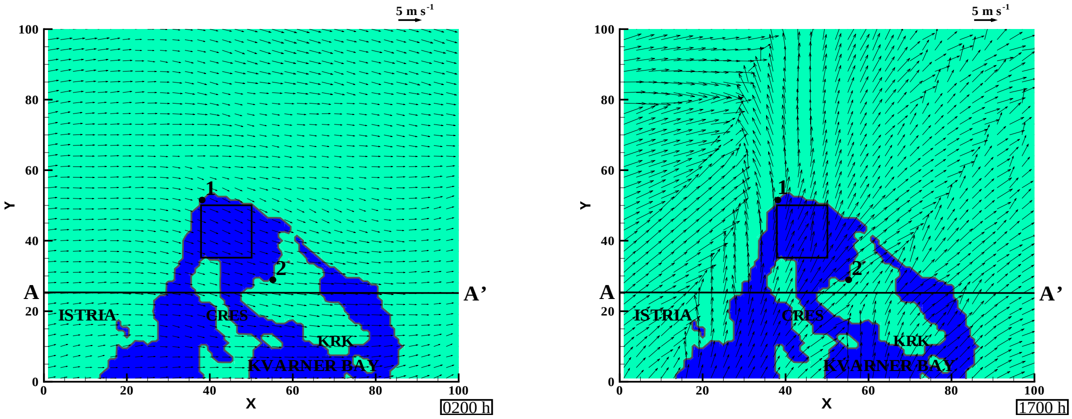

Figure 3. Same as in Fig. 1 but for T1 test (simulation with the idealised topography and real synoptic forcing).

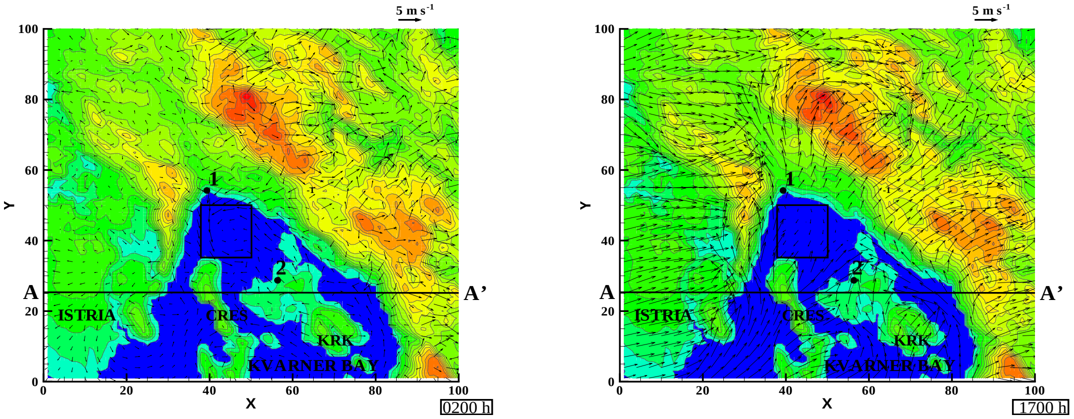

Figure 4. Same as in Fig. 1 but for T2 test (simulation the real topography but without synoptic forcing).

The T1 test has shown that eddies are mostly a mesoscale response to the coastline shape and topography and are less influenced by the background flow (compare Figs. 3,4). To compare the results between sensitivity tests and the control run, a time displacement of the main Istrian CZ along AA’ cross-section is determined. Removing the mountains, T1 displays that the differential heating and the shape of the peninsula have crucial role in forming of such CZ pattern over Istria. The main CZ develops relatively close to the eastern Istrian coast compared to the control run and the additional CZs appear with shorter lifetimes (Fig. 3b). The influence of the idealised synoptic conditions in T2 test displays the dominance of the western SB. This domination is observed especially in the late morning hours (Fig. 4b) influencing on the CZ speed. In T1 test, the completely conserved geometry of the coastline and islands is not enough to generate the CZ above the NE part of the island of Krk. This test demonstrates that the channelling effect in the wind field and LLJ also does not occur between the island and mainland (Fig. 3b). The absence of the CZ along the NE part of the island of Krk has pointed out the major topographic effects. The T2 test displays all characteristic features of the CZ and LLJ as in the control run (Fig. 4b).

4. CONCLUSION

A 3D nonhydrostatic model was used to study a very complex but still typical summertime wind regime along the NE Adriatic coast. The results showed the model’s ability to reproduce SB circulations with specific mesoscale characteristics such as mesoscale eddies, CZ and the LLJ. Besides the control run, two additional sensitivity tests were performed to determine the roles of the various topographical and synoptic features. The comparison of the two additional sensitivity tests with the control run showed that the orography had strong influence on both the initial position and the number of the Istrian CZ. More than the Istrian CZ, the CZ over the island of Krk (and LLJ) was highly dependent on the terrain height and coastal geometry. Mesoscale eddies occurred inside the Rijeka Gulf during 24 hours as a sole result of the topography.

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