ON THE BORA BREAKTHROUGH NEAR A MOUNTAIN GAP

Alexander Gohm and Georg J. Mayr

Institute for Meteorology and Geophysics, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria
E-mail: *alexander.gohm@uibk.ac.at*

Abstract: This study investigates the onset phase of a strong Adriatic bora on 04 April 2002 with high-resolution numerical modeling and observations. The airborne measurements were taken with the German Aerospace Center's (DLR) Falcon aircraft within the framework of the EU-funded CAATER Programme 2001. The target area is a ∼20-km wide mountain gap embedded in the Dinaric Alps, which favors strong jet-like winds. The model indicates a delay of the bora breakthrough at the coast of up to three hours between the center and the edge of the gap. During this period the wind field downstream of the gap is highly three-dimensional and transient. Near the gap center, a low-level jet is observed with winds exceeding 30 m s^{-1}. Near the edge of the gap, the model shows flow separation and the formation of a low-level rotor with weak but reversed surface winds underneath trapped gravity waves. This complex flow configuration with strong spatial variations in the wind field leads to horizontal and vertical wind shear in the vicinity of Rijeka airport on Krk Island, which represents a potential hazard for air traffic.

Keywords – *CAATER, bora, gap winds, wind shear, hydraulic jump, rotor, gravity wave, modeling, airborne lidar*

1 INTRODUCTION

1.1 The phenomenon

During recent years, especially since the Mesoscale Alpine Programme (MAP), the study of bora winds has experienced a renaissance (e.g. Grubišić 2004; Gohm and Mayr 2005). The application of high-resolution measurement techniques such as airborne remote sensors and of numerical simulations has made it possible to study small-scale aspects of these downslope windstorms, including the role of boundary layer effects and the generation of potential vorticity banners. The present work focuses on the investigation of the highly complex wind field pattern near a mountain gap during the breakthrough phase of the bora on 04 April 2002 and highlights the potential hazard of the associated wind shear for air traffic at a nearby airport. The target area of the investigation is shown in Fig. 1(a) with a close-up of the vicinity of the gap in Fig. 3(a). The gap is represented by a pass (∼1 km) embedded in the ∼1.5 km high coastal mountain range.

1.2 Model and measurement description

The numerical model used in this study is the Regional Atmospheric Modeling System (RAMS) with the same setup as in Gohm and Mayr (2005) except for the innermost nested grid (domain 6), which is now located further north. Model domains 5 and 6 have horizontal mesh sizes of 800 and 267 m and are shown in Fig. 1(a) and 3(a), respectively. The model results are compared with airborne remote sensing observations and with surface wind measurements. The aircraft measurements on board of the DLR Falcon were conducted with a downward looking aerosol backscatter lidar which had become available through the EU-funded CAATER Programme 2001.

2 RESULTS AND DISCUSSION

2.1 Low-level wind field

The simulated wind field at 300 m above sea level (MSL) of domain 5 shortly after the time of the breakthrough of the bora is shown in Fig. 1(a). Two bora jets with northeasterly winds exceeding 25 m s^{-1} emanate over the sea downstream of gaps in the Kapela and the Velebit mountain range, respectively. They are separated by a wake region with winds below 15 m s^{-1}, which is typically observed downstream of the southern tip of the island of Cres (see e.g. Gohm and Mayr 2005). Winds between the island of KrK and the mainland are

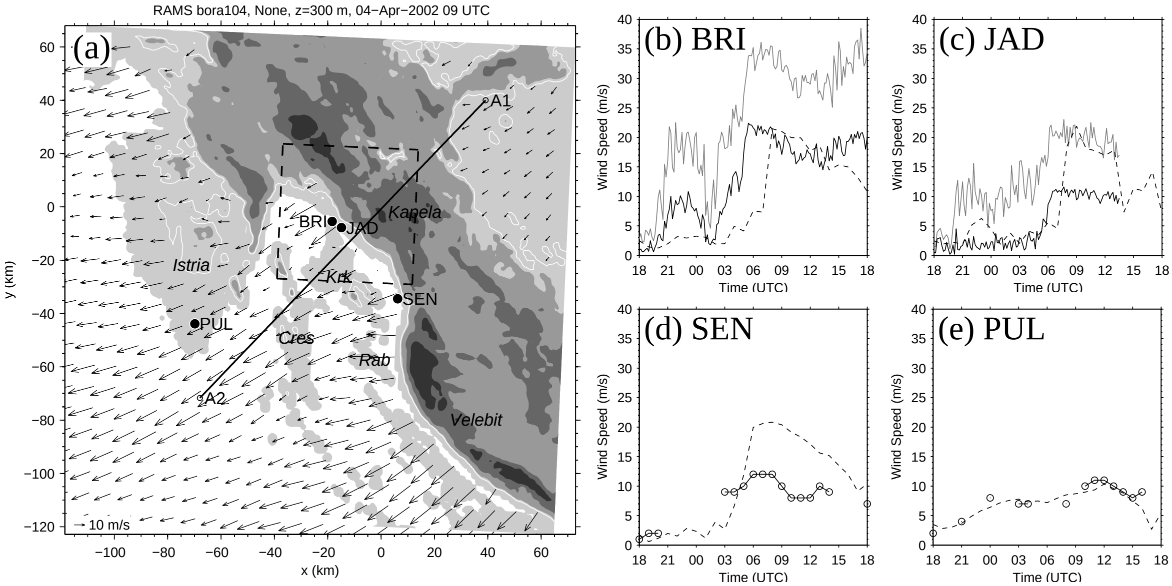

Figure 1: (a) The target area (model domain 5) with the orography of the northern part of the Dinaric Alps (gray shaded elevation contours starting at 0 m with 400 m increments; white contour line at 300 m MSL) and simulated horizontal wind vectors at 300 m MSL (see lower left corner for reference vector) for 09 UTC 04 April 2002. (b)–(e) Comparison between observed (solid lines) and simulated (dashed lines) surface wind speed (m s^{-1}) for a 24-hour period starting at 18 UTC 03 April 2002. Solid black (gray) lines in (b)–(c) are observed sustained wind speeds (wind gusts) from automatic weather stations and lines with circles in (d)–(e) are wind speeds from SYNOP stations. Observed (simulated) winds are for (b) Krk Bridge (BRI) at 60 (63) m MSL, (c) Jadranovo (JAD) at 2 (83) m MSL, (d) Senj (SEN) at 28 (31) m MSL, and (e) Pula (PUL) at 63 (98) m MSL. Line A1A2 in (a) indicates the cross-section shown in Fig. 2. A dashed box encloses model domain 6 shown in Fig. 3(a). Three-letter labels indicate locations of observation sites. Landmarks are italicized.

weak, which indicates that the bora breakthrough has not yet occurred everywhere along the coastline. But strong bora winds are already present at the famous bora station of Senj.

The comparison of the simulated surface wind speed with observations from four weather stations is shown in Fig. 1(b)–(e). The bora breakthrough, marked by a rapid increase of wind speed, generally occurs in the morning hours of 04 April 2004 and is observed earliest at Senj (SEN), followed by Krk Bridge (BRI) and Jadranovo (JAD). At Pula (PUL) no clear breakthrough is evident as winds are generally weaker and only show a gradual increase. Winds are strongest at BRI (observed gusts exceeding 35 m s^{-1})—a site 60 m above ground level. A clear temporal phase error between the simulated and observed time of the breakthrough is evident, with the model being about 1 to 3 hours too late depending on the location. Discrepancies between the observed and simulated wind speed magnitude may be related to a vertical offset between the true measurement height and the model level and to local differences between true and model terrain. Despite the phase shift we believe that the model results are suitable to elucidate flow details of the simulated breakthrough phase.

2.2 Comparison of model and aircraft data

Figure 2 shows a comparison of the simulated and observed flow across the Dinaric Alps at 07 UTC along the transect A1A2 as indicated in Fig. 1(a). Below about 1.2 km MSL the model isentropes and the observed backscatter field both indicate a convective mixed layer (CML) upstream of the mountain ridge. The CML top increases slightly towards the crest. The simulated stable inversion layer (SIL), above the CML and below about 3 km MSL, corresponds with several vertically staggered aerosol and/or thin cloud layers (ACL). The general structures of the simulated SIL and of the observed ACLs agree well: they indicate gravity waves excited from individual peaks and strong descending motions to the lee of the main ridge. Above 3 km wave activity is weak due to directional wind shear in the background flow which keeps the bora flow shallow. Wave breaking above the leeward mountain slope is apparent in the model, which is—together with flow descent—presumably the reason for the disappearance of the well defined ACLs downstream of the mountain. Separation of the flow from the lee slope indicates that the low-level bora winds have not yet penetrated down to the coast. Reattachment of the flow to surface occurs near the first island. The observations cannot fully support this

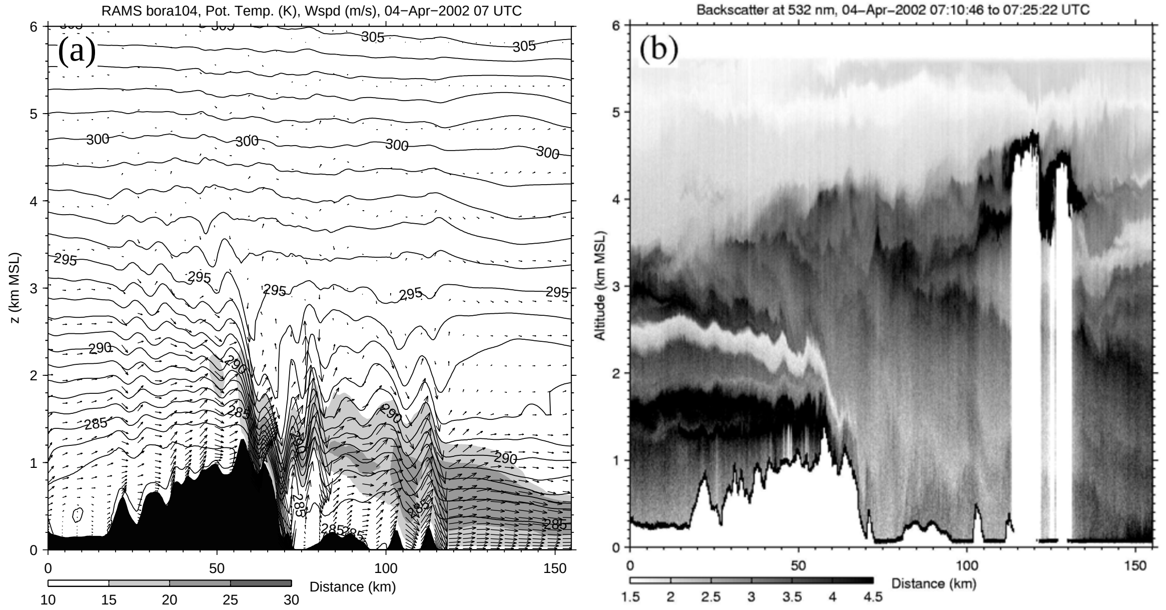

Figure 2: Vertical transect across the Dinaric Alps along leg A1A2 (see Fig. 1(a)): (a) The simulation at 07 UTC and (b) the observed range-corrected backscatter intensity (arbitrary units) at 532 nm between 0711 and 0725 UTC 04 April 2002. (a) Contour lines of potential temperature (K) with 1 K increments, gray shaded contours of horizontal wind speed (m s^{-1}) with 5 m s^{-1} increments, and wind vectors showing the components along the cross-section. Orography is black in (a) and white in (b).

feature due to weak backscatter intensity. However, the general descent of isentropes, which leads to strong flow over the ocean far downstream of the coast, also shows up in the descent of the weakly defined ACL top.

2.3 Wind shear, hydraulic jump, and wave-induced rotor

The flow structure at 09 UTC near one of the two gaps in the Kapela mountains is illustrated in Fig. 3. This gap is ∼20 km wide and located about 20 km upstream of the airport of Rijeka on the northern tip of KrK Island (see Fig. 3(a)). The horizontal wind field at 300 m MSL in Fig. 3(a) shows stronger flow (exceeding 30 m s^{-1}) through the gap and over the airport than near the two gap edges. Especially near the southern edge a wake with almost zero winds is apparent. The approach corridor of the southeast-to-northwest aligned runway passes this wake region. An approaching aircraft would therefore encounter strong shear due to rapidly increasing cross winds close to the airport. Regions of strong shear are associated with turbulence and therefore represent a potential hazard for air traffic, especially during the final approach procedure close to ground.

A vertical transect parallel to, but slightly east of the approach corridor is shown in Fig. 3(b). Strong low-level flow is apparent in the northwestern part of the cross-section which represents the jet flow through the mountain gap. A potentially cold air dome with weak low-level winds in the southeastern part represents the wake near the gap edge. The flow in the wake is reversed with respect to the bora wind direction. Figure 3(c) illustrates the flow through the gap center. The bora jet has already reached the island of KrK. The breakthrough in this transect occurred between 07 and 08 UTC. The bora front is marked by a hydraulic-jump-like feature. In a transect about 10 km further southeast, i.e. near the gap edge, the bora flow has not yet reached the coast (Fig. 3(d)). There, the breakthrough is simulated between 10 and 11 UTC, i.e. about 3 hours later. The reason is flow separation due to steeper and higher (at least further upstream near the crest) terrain and the formation of trapped lee waves. Consequently, a mountain-wave-induced rotor forms near the coast, similar to the study by Doyle and Durran (2002), which explains the cold air dome and the reversed low level flow in Fig. 3(b). The dimensions of the rotor are about 2, 4, and 10 km in the vertical, along-stream, and across-stream directions, respectively. The lifetime of the rotor is 2 to 3 hours and essentially ends with the bora breakthrough.

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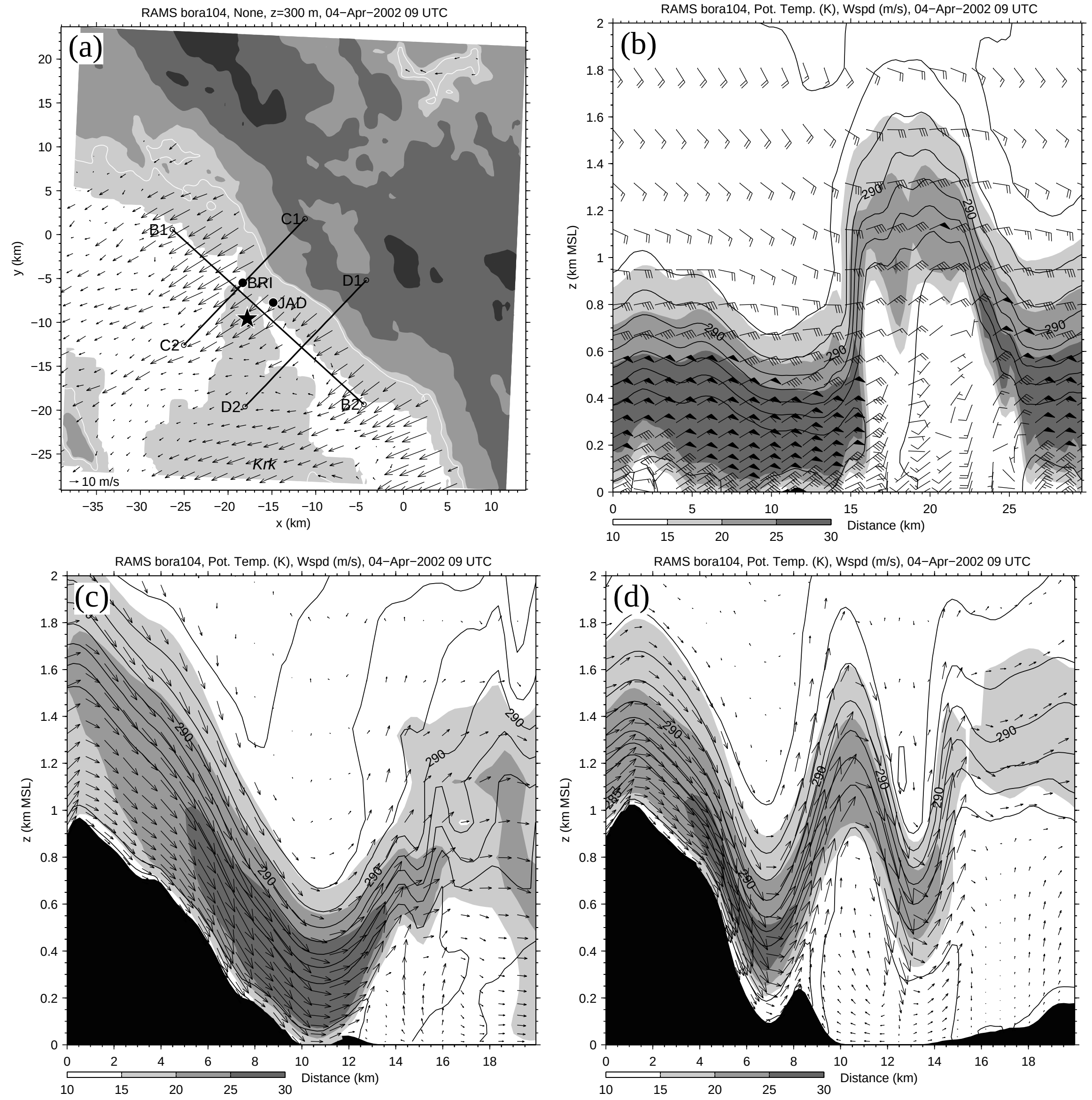

Figure 3: Model data of domain 6 for 09 UTC 04 April 2002 illustrating the bora breakthrough with a hydraulic jump as well as a wave-induced rotor near the coast downstream of a mountain gap: (a) Wind field and orography as in Fig. 1(a). Solid lines B1B2, C1C2, and D1D2 indicate vertical transects shown in (b), (c), and (d), respectively. (b)–(d) Potential temperature, wind speed, and orography as in Fig. 2(a). Barbs for horizontal winds (half barb, full barb, and triangle for 5, 10, and 50 knots) are shown in (b) and wind vectors for the wind components along the cross-section in (c) and (d). The airport of Rijeka on KrK Island is indicated with a star in (a).

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