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A review of recent advances in understanding the meso- and microscale properties of the severe Bora wind

By BRANKO GRISOGONO* and DANIJEL BELUŠIĆ, *Andrija Mohorovičić Geophysical Institute (AMGI), Department of Geophysics, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia*

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ABSTRACT

A gusty downslope windstorm that blows at the eastern Adriatic coast is called bora. Similar winds exist at many other places on virtually all continents. Related hourly mean wind speeds surpassing 20 m s^{-1}, with gusts reaching up to 50 or even 70 m s^{-1}, in the coastal mountain lee areas are common (hurricane speeds). There has been substantial progress in bora observations and measurements, understanding, modelling and its more detailed prediction during the last 25 yr. It was generally thought before that bora was a falling, mostly thermodynamically driven wind; however, (severe) bora is primarily governed by mountain wave breaking. Understandings of bora interactions and influences on other processes have taken place as well, most notably in the air-sea interaction, but are not completed yet. The overall progress mentioned would not be possible without airborne data, non-linear theory and advances in computational techniques, most notably mesoscale numerical models. Some gaps in bora knowledge are also indicated, for example, dynamical transition from weak to moderate to strong to severe bora flows, where the latter are the main subject here, and vice versa. Moreover, the role of the boundary layer and waves on the upwind side of the bora evolution and the consequent lee side flow structures are inadequately understood; this is especially so for bora at the southern Adriatic coast. The focus here is on stronger bora flows at the NE Adriatic coast.

1. Introduction

Peer-review studies of bora wind go back to at least 19th century (e.g. Mohorovičić, 1889). Andrija Mohorovičić discovered the discontinuity between the Earth crust and mantle[1] after his pioneering work on bora rotor clouds (e.g. Grubišić and Orlić, 2007). The only well recognized book dedicated solely to bora wind was edited quite some time ago by Yoshino (1976). A few major advances in the understanding of bora flows have appeared since then, in particular due to the results of ALPEX (e.g. Smith, 1987) and MAP campaigns (e.g. Doyle and Durran, 2004; Grubišić, 2004; Volkert et al., 2007) as well as numerical simulations (Durran, 1986; Klemp and Durran, 1987; Enger and Grisogono, 1998; Lazić and Tošić, 1998; Jiang and Doyle, 2005; Gohm et al., 2008; etc.). While we are waiting for a new monograph yet to be written about bora and its effects, many scientists in mountain and even coastal meteorology and oceanography would like to see at least a short up to date review of progress in the research about bora during, for example, the last few decades. Most recent efforts have been put into the bora mesoscale and microscale studies; hence, we focus on these studies, instead of trying to review the whole of bora findings, which would demand a dedicated book. The intention of this paper is to skim through some more recent meso- and microscale findings related to strong to severe bora flows at the NE Adriatic coast. Namely, there are also weak to moderate bora flows, that have not been studied very much and which are out of the scope of this work.

Figure 1 depicts the Adriatic region, which is associated with the bora flow. A year before ALPEX, Jurčec (1981) summarized typical synoptic and mesoscale characteristics of bora flows. The classic bora blows from NE quadrant over the coastal mountains that are ~1-km high, usually bringing cold and dry (or relatively drier) air to the Adriatic compared with that residing at the coastal lee side. The associated synoptic setup for the onset, persistence and cessation of bora is well known; this is related to the position of cyclonic flow nearby the Adriatic Sea, or/and high-pressure centre around the central Europe (e.g. Heimann, 2001). The cyclone over the sea draws the lower tropospheric air from the continent over the coastal mountains, which most easily passes between the eastern Alpine outskirts and the broad Bosnian–Balkan mountains. Similarly, synoptic high pushes the air from the broader Pannonian area and the

*Corresponding author.
e-mail: bgrisog@gfz.hr
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[1]Such discontinuity also exists on the Moon and Mars, and it is thus also called after his name, Moho discontinuity. The Geophysical Institute at the University of Zagreb is called after him (AMGI).

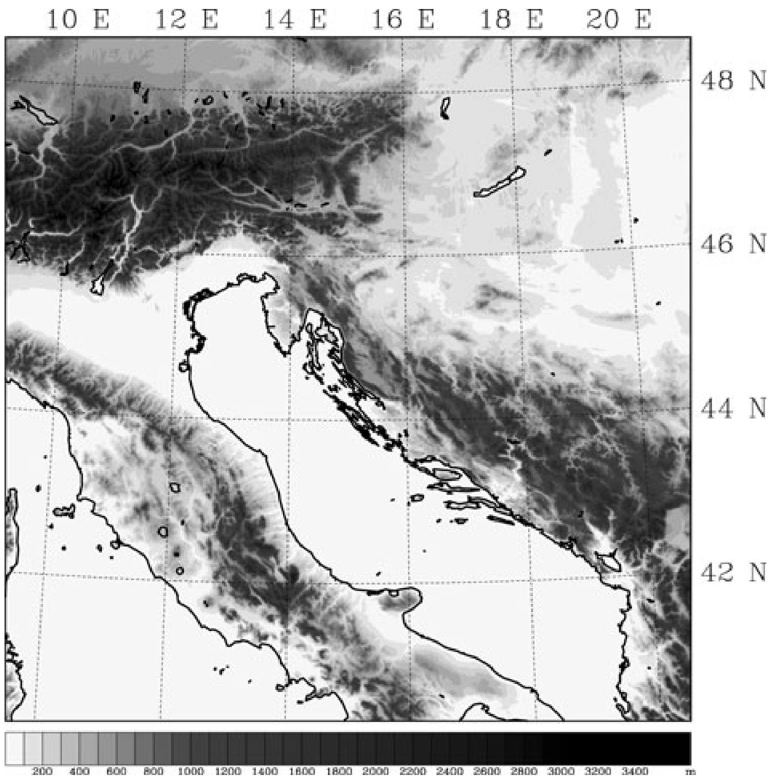

Fig. 1. The Adriatic Sea and the surrounding mountains related to the bora flow at the eastern Adriatic. The terrain height is shaded every 100 m. The mountain of Velebit is in the middle. Bora blows from NE to SW.

central Europe toward the Adriatic over the coastal mountains. A cold front passage itself may also induce a relatively short lasting bora.

Depending on the details of the synoptic setup, bora may sometimes appear with clouds as well; in such cases it is often called 'dark bora' (varying from the more typical 'clear bora'), see, for example, Jurčec (1981). Some of bora statistics (classification, intensity, duration, frequency of occurrence, etc.) may be found in, for example, Poje (1992). Bora is more vigorous and frequent in the wintertime season, when it typically lasts for several days. Synoptic facts about upper layers and near-surface flows associated with bora are found in Yoshino (1976), Jurčec (1981), Ivančan-Picek and Tutiš (1996); Heimann (2001) and Horvath et al. (2006, 2008). Shallow bora (e.g. Petkovšek, 1990; Gohm et. al., 2008) occurs when the flow is confined in the lower troposphere only, separated by, for example, a strong synoptic inversion from the flow aloft; a typical example is bora associated with a ridge from the Siberian anticyclone. Another example of bora (sub)synoptic generation is the Alpine lee cyclogenesis, primarily around the gulf of Genoa, and its consequent evolution, for example, a daughter cyclone in the Adriatic, that produces relatively lower pressure over the Adriatic Sea which then bora flow tries to fill in. Depending on the intensity and evolution of such lee-cyclogenesis and its (lack of) synchronization with the upper tropospheric flow, either shallow or deep bora can be produced. Deep bora blows throughout the troposphere, without strong synoptic inversions and significant geostrophically balanced wind vector alterations. It seems that the deep bora wind is on average weaker than the shallow bora wind, but a systematic climatology is lacking. Recent evaluation of bora effects, from the synoptic scale to mesoscale, on the Adriatic Sea is in Dorman et al. (2007).

Bora is a vigorous flow, a type of severe downslope windstorm, which varies in space and time and the location of occurrence. It greatly affects or even stops virtually all human and cargo transportation in the area of its occurrence, as well as altering some other human activities. One typical bora record is shown in Fig. 2, taken in the town of Senj (45.2°N, 13.8°E), famous for bora in terms of its severity, persistence and its effects. The along-bora wind component is displayed. Bora-type flows occur at least at a few tens of regions in the world (e.g. Lilly, 1978; Jurčec, 1981; Ágústsson and Ólafsson, 2007); nowadays one may find over 25 bora-related places in the world by using, for example, internet. These include but are not limited to: Southern California, Rocky Mountains, Western slopes of the Andes, Austria, Iceland, New Zealand, Sumatra, Japan, Indonesia, Kurdistan, Russia, etc. Hence, data records similar to that in Fig. 2 are obtainable from other mountainous areas. In general, bora has been studied much more at the northern than the southern Adriatic coast, partly because the Adriatic coast around the mountain of Velebit, that is, around ∼45°N–46°N and 15°E–16°E, is somewhat less complex than the southern coast. The northern part of the coast including Velebit has less of the upwind mountains disturbing the incoming flow, and it

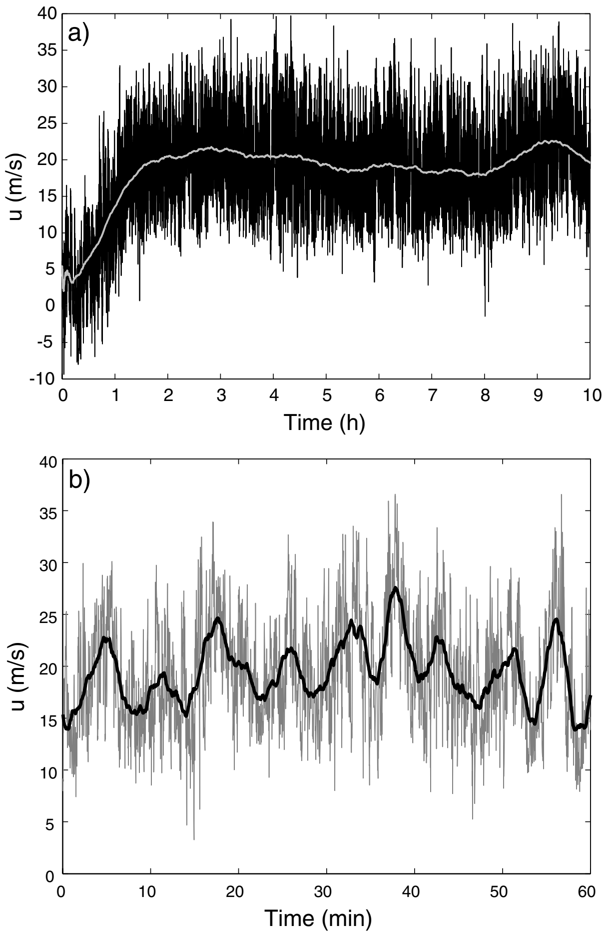

Fig. 2. The along-bora wind component in Senj: (a) 1-s time-series of a part of a bora episode (black), with 1-h mean superimposed (grey). Time is in hours after 00 LST, 8 Dec 2001. Also (b) 1-h expanded view (6th hour of the episode) of the 1-s time-series (grey), with 2-min mean superimposed (black) showing pulsations.

possesses fewer gaps (passes), coastal valleys and significant estuaries than its less studied southern counterpart. Next, we discuss the changes in the understanding of the Adriatic bora during the last 20 to 25 yr, the current research and possible future scientific avenues pertaining to bora meso- and microscale features.

2. The change of concept

The basic understanding of bora severe wind changed, from a more of a basic 'katabatic-type' perspective to a hydraulic-like flow, often containing the orographic wave breaking as the main generating mechanism. In other words, the concept developed from the plausibly attractive idea 'the bora as a fall wind', where the parcel accelerates downslope due to its relatively larger density (lower temperature), to orographic wave breaking as the key mechanism for severe bora. Before ALPEX, it was thought that bora belongs to the class of katabatic winds, such as gravity flows (Yoshino, 1976; Jurčec, 1981). The mesoscale structures related to such winds were thought to be, for example, upstream blocking of cold air and interactions of mountain ridges with stable boundary layers including slow cross-isobaric flow near the surface. However, simple katabatic flows may not produce sustained mean wind speeds above $\sim$20 m s^{-1} and more, related to downslope windstorms, simply because such speeds require huge surface potential temperature deficits. Namely, the katabatic wind speed is proportional to this temperature difference. Therefore, the temperature difference between a cooled surface by radiation and the ambient air at the same height required to obtain katabatic wind speeds of $\sim$20 m s^{-1} is about $\sim$25 °C (e.g. Egger, 1990; Grisogono and Oerlemans, 2001). Another problem with the katabatic mechanism is the elevation of the wind speed maximum that is much too low compared with that in severe bora, the latter being at $\sim$0.5 km above the ground.

On the other hand, linear wave theory was inadequate to describe bora and the associated large mesoscale pressure gradient, large lee-side wind speeds and simultaneous stagnations above the mountain top (i.e. non-linear effects). At the time of Yoshino (1976) book on bora, mesoscale meteorological community still struggled about a consistent wave dynamics, most notably about the type and role of the upper boundary condition and the role of non-linear processes (Smith, 1979b, 1989; Nappo, 2002). Since the ALPEX project, the conceptual change about the basic bora understanding began (Smith, 1987). After MAP, that is, $\sim$15 to 20 yr after ALPEX, 3-D non-local bora structures came into view. Most of these bora flow aspects are essentially induced by orographic wave breaking and mesoscale pressure gradients, consisting of largely mountain-perpendicular lee jets[2] and wakes, rotors and jumps (Grubišić, 2004; Gohm and Mayr, 2005b; Jiang and Doyle, 2005; Belušić et al., 2007; Smith et al., 2007; Gohm et al., 2008).

2.1. Overview

The main breakthroughs in studying strong-to-severe bora are seminal papers by Smith (1985, 1987) and Smith and Sun (1987), followed by that of Klemp and Durran (1987). Essentially, these authors show that strong-to-severe bora is not a typical falling, katabatic-like wind (Yoshino, 1976; Jurčec, 1981), but instead, it belongs to a class of lee-side severe downslope windstorms (e.g. the Boulder windstorm). Various subtypes of falling wind may still apply locally, for instance, when only the surrounding of Senj has light-to-moderate bora. This old concept about bora as a thermodynamically (katabatically) driven wind might also still work at the onset or decaying stage, when bora is not

[2] A few kinds of jets can be involved in bora flows: the lee side shooting flow, most often emanating from the mountain gaps; lee jets from the mountain flanks; elevated coast-parallel jets and the incoming jet stream.

severe and is not spread over hundreds of kilometres along the coast. Since we address here strong to severe bora occurring over significant parts of the Adriatic coast, apparently there is a primary mechanism determining this downslope windstorm, that is, wave breaking. Meanwhile, there are other views on conceptual models for downslope windstorms. These other models emphasize the importance of, for example, small-scale instability and/or flow separation acting in concert (e.g. Farmer and Armi, 1999) and determining the time-dependent flow evolution toward eventual high-drag state. Another model stresses the role of non-linear wave-ducting mechanism prior to the hydraulic jump formation (e.g. Wang and Lin, 1999). The corresponding early sequence of detailed events toward establishing severe bora state, for example, the upwind boundary layer evolution, has not been well documented yet.

Internal (non-linear) hydraulic theory, or simply hydraulic theory, accounts for upslope acceleration and streamline descent, a coincidence between the uppermost descending streamline and the wind stagnation or reversal in the mixed layer above the lee, an elevated flow decoupling and the inversion splitting and a fast downslope flow below the mixed layer. The key difference between the katabatic and the hydraulic theory of bora is the following. In basic katabatic flows, the cold (heavier) air is produced locally by a radiation deficit at the surface (e.g. Egger, 1990; Whiteman, 2000; De Wekker and Whiteman, 2006). Katabatic flows may reach a local equilibrium in which the heat loss due to the surface temperature deficit is balanced by, for example, turbulent friction (or/and advection, etc.). This kind of balance is not the case for bora. Whereas the air in katabatic flows moves downslope under the influence of gravity, in hydraulic flows gravity relates to significant pressure gradients, which generate accelerations. Whereas the speed in katabatic flows would diminish eventually as the air moves uphill, in hydraulic-like flows, the inversion depth already begins to drop upstream (e.g. Smith, 1987), causing a favourable pressure gradient. Thus, the flow accelerates (which is contrary to an upslope deceleration occurring for a katabatic flow).

Hydraulic theory is deployed as a conceptual model for treating a large set of strong bora cases (Smith, 1987; Klemp and Durran, 1987; Gohm et al., 2008); however, the orographic wave breaking and other stratified and 3-D effects also play decisive roles (e.g. Durran, 1986; Miranda and James, 1992; Smith and Grønås, 1993; Ólafsson and Bougeault, 1996; Hunt et al., 1997; Smith, 2002; Grisogono and Enger, 2004; Jiang and Doyle, 2005). If oversimplified, one may say that bora may blow over moderately high mountains, $\sim$1 km in the average maximum height, so that the airflow is only partially blocked, whereas large, steep waves appear above the mountain, overturn and eventually break. This process usually leads to a hydraulic jump-like structure in the lower lee side associated with eddies. Inspired by works of Ronald B. Smith, additional confirmation and new details about bora hydraulics appeared in Bajić (1991), as well as new questions pertaining to 'less-of-hydraulics' bora flows (and also where shallow water theory is apparently less successful in modelling bora). The latter flows may occur at the southern Adriatic coast (Jurčec and Visković, 1994; Ivančan-Picek and Tutiš, 1996), presumably due to the additional terrain complexity, such as numerous mountain gaps. Systematic gap-flow analysis for the Alpine region is summarized in Mayr et al. (2007); details of bora-related gap flows remain to be studied in the (especially southern) bora region. Successful analogies between the Alpine gap-flow cases, usually related to föhn wind (e.g. Armi and Mayr, 2007; Mayr et al., 2007), and the Dinaric Alps gap-flow cases, associated with bora, are very few (Gohm et al. 2008). The reasons for this are at least two-fold: the Alps were much better covered with the observations during the MAP than the bora region has ever been, thus, the gap-flow parameters could have been determined properly only in the former case; second, the mountain character is different. The Alps are steeper, higher, broader and longer, containing deeper and sharper major gaps/passes. Gap-flow effects certainly amplify bora locally (e.g. Gohm et al. 2008). These flows might also play important roles in the early stage as well as diminishing phase of bora. Furthermore, this mechanism may govern more local and moderate bora cases. While stressing local importance of gap effects in a bora case, Gohm et al. (2008) still find the wave breaking as the key mechanism for the strong bora.

Most often the presence and intensity of orographic wave breaking governs the bora severity (Klemp and Durran, 1987; Enger and Grisogono, 1998). Therefore, a thicker tropospheric layer must be involved determining the upwind flow, yielding a relatively small internal Froude number, which for continuously stratified flows is better described as a non-linearity parameter, $Nlp = U/(NH)$, where U is the mean wind speed perpendicular to the mountain of the maximum height H and N is buoyancy frequency (in 2-D linear flows, NH is also the magnitude of hydrostatic wave perturbation velocity component perpendicular to the ridge, see e.g. Nappo, 2002; Holton, 2004). This Nlp is the inverse of the non-dimensional mountain height, which is often invoked in studies of non-linear orographic flows (e.g. Durran, 2003) (Meanwhile, Froude number, Fr, for a single-layer shallow-water flow is defined as $Fr = U/C_P$, where C_P is the phase speed of gravity waves). The definition has various extensions, depending on the particular use and the number of combined shallow layers (e.g. Armi and Mayr, 2007). Importance of the state of the upwind flow (Pierrehumbert and Wyman, 1985; Smith, 1985, 1987; Klemp and Durran, 1987; Glasnović and Jurčec, 1990) cannot be overstressed for the development of bora-type flows. The wave breaking occurs roughly around $1/4 < Nlp < 1$ (e.g. Durran, 1986, 1990; Smith, 1987; Castro and Snyder, 1993; Grisogono, 1995; Ólafsson and Bougeault, 1996; Dörnbrack, 1998; Epifanio and Durran, 2001). Note that Nlp is straightforward to estimate only for relatively simple flows without significant changes in U and/or N. In more complex flows, one may have to deploy, for example, an average background Nlp, which might vary with height, and various local Nlp

definitions describing the flow transcriticality (e.g. Durran, 2003; Holton, 2004; Armi and Mayr, 2007).

Critical layer (or level) is the layer where the phase speed of buoyancy waves equals the ambient wind speed in the direction of wave propagation. Mountain waves are stationary; thus, the critical layer is located at the height where the cross-mountain wind speed is zero. Since wave breaking regions are stagnant, these regions are closely related to critical layers. Bora severity does not depend on whether the critical layer is flow-induced (i.e. non-linear) or imposed by incoming flow. Most of bora features mentioned insofar pertain to more realistic stratified flows, which are more difficult to understand than shallow-water flows. Apparently, large-amplitude mountain waves, which are progressively steepening and eventually breaking, are responsible for severe bora. Such waves are not amenable to analytic treatment except in highly idealized conditions; thus, one may consider various cumulative (integral) flow properties and constrains in relation to these waves. Bora-like flows may be studied by estimating, predicting and analysing the associated orographic wave drag. Qualitatively speaking, wave drag tells us about the amount of waviness in the flow. This is a bilinear or quadratic (somewhat similar to wave energy) measure of wave activity, which is ultimately related to orographic momentum transfer and consequently to the near-surface flow severity (e.g. Smith, 1979a; Tutiš and Ivančan-Picek, 1991; Kim and Mahrt, 1992; Grisogono, 1995; Ivančan-Picek and Tutiš, 1995). The latter authors indicated that severe bora may yield pressure drag, probably to a large extent made of wave drag, several times larger than the wave drag in stable no-bora conditions. Such a high-drag state, which is absent in simple katabatic flows or weak-bora conditions (perhaps related to nearly linear waves), is most often associated with orographic wave-breaking, the latter frequently having its hydraulic analogy. Namely, strong downslope flow due to wave breaking is similar to the hydraulic lee-side flow response forced by a sharp inversion layer.

Klemp and Durran (1987) also showed that non-hydrostatic effects are less than of secondary importance for the bulk structure of vigorous bora. Their non-linear shallow-water model results, associated with hydraulic theory, agreed nicely with those from their non-hydrostatic model simulations. Knowing that the hydrostatic approximation is valid up to a second order for shallow-water flows (e.g. Pedlosky, 1987), it is straightforward to accept the negligibility of non-hydrostatic effects on bora basic dynamics, that is, on its essentials. Similar reasoning as for non-hydrostatic effects may apply for radiative and moist processes (e.g. Ivatek-Šahdan and Tudor, 2004); these effects are at best of secondary importance for the essence of bora, even for many of the dark bora cases. For light to moderate bora flows, this issue is not settled yet.

A review, related to downslope windstorms at that time, is in Smith (1989) and Durran (1990). Further improvements of the theory are in Schär and Smith (1993a, b) and Schär and Durran (1997), deploying effectively the PV concept within non-linear orographic wave theory. An avenue in the understanding of severe downslope windstorms can also be found in Scinocca and Peltier (1994). Hydraulic theory (e.g. Long, 1954; Houghton and Kasahara, 1968; Durran, 1990) was invoked for bora-type flows even before Smith (1987), but these results were never published in peer-review literature. Ivo Lukšić, from the Croatian Weather Service, built a tank to study bora in 1960s, proceeding with it in 1970s, apparently using a two-layer *Fr* to characterize this flow (see e.g. references in Jurčec, 1981). There is extended literature about this pioneering work in Croatian language and certain conference proceedings, but the local leading scientists of that time did not recognize the significance of this early work (Ivo Lukšić pioneering equipment is recently displayed at AMGI, Zagreb).

2.2. *Essence of bora*

Let us briefly summarize the basic bora dynamics, as understood after the change of concept (hence, simple katabatic flows are excluded here). We start with 2-D effects and then proceed with 3-D findings. The interaction of the incoming flow with the mountain, through the *Nlp* transcriticality, enables the appearance of delimited shooting flow in the lee, which is so typical for bora (e.g. Smith et al., 2007). Given the constant mountain height, this depends on the upstream stratification and wind speed structure and may be accomplished in one of, or through a combination of, the following three ways (e.g. Durran, 2003).

(1) Appearance of the wave-breaking induced critical layer, which is possible for any upstream flow, for example, a constant profile of N and U, provided that $Nlp < 1$.

(2) Existence of the upstream low-level critical level, which enables wave breaking due to non-linear amplification of the vertically propagating buoyancy waves as they approach the level (e.g. Smith et al., 2007).

(3) Existence of the near-mountain-top temperature inversion (e.g. Vosper, 2004).

Klemp and Durran (1987) have shown that the mechanism (1) is essential for the bora appearance. However, bora upstream structure is frequently characterized by (2) and/or (3). All the three cases stated above enable the existence of a layer that delimits the lee-side, mountain-perpendicular low-level jet (LLJ) flow (they refer to this kind of LLJ as the shooting flow) from the region aloft. In these conditions, the flow can be conveniently described by the hydraulic theory (Smith, 1985, 1987). However, the reality introduces additional 3-D effects such as flow splitting and possible lee-side eddies. The most prominent one is the existence of the irregularities in the height of the mountain range, namely the mountain peaks and gaps. It has been shown that these features are essential for the structure of the 3-D flow. Namely, the mountain gaps are associated with the LLJs, emanating from the gaps as relatively stronger shooting flows, whereas the peaks are related to the wakes. This structure has been noted

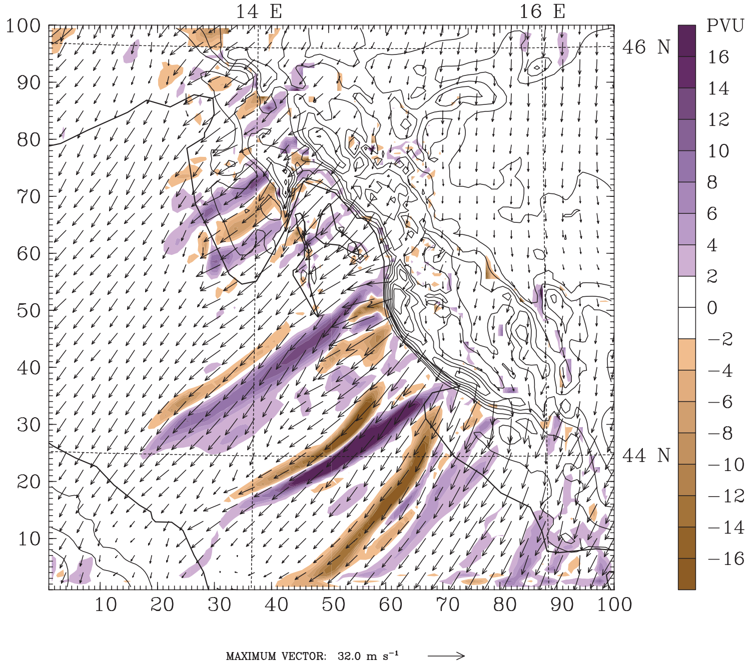

Fig. 3. Modelled potential vorticity banners at 700 m above sea level and wind vectors near the surface at 00 UTC, 15 November 2004 (cf. Belušić and Klaić 2006). The domain has 100 × 100 gridpoints (see axes) at 3-km resolution. Similar banners were observed and modelled by Grubišić (2004) and Jiang and Doyle (2005).

for both severe bora cases (Jiang and Doyle, 2005; Belušić and Klaić, 2006; Gohm et al., 2008) and weak bora cases when the hydraulic dynamics does not govern the bora flow (Gohm and Mayr, 2005a). The latter are usually 'deep' bora cases, contrary to 'shallow' bora that is most often associated with synoptic inversions above the mountain top.

The flow layering in the vertical occurs as a manifestation of a very large-amplitude orographic wave that is usually breaking. A part of the flow in the lee and below the wave breaking is highly accelerated producing the downslope shooting flow. Synoptic inversions enhance the layering; thus, these are important but not the essential ingredients of bora severity (Klemp and Durran, 1987). As the air flows over higher coastal-mountain peaks, hydraulic jumps are released in their vicinity (Grubišić, 2004; Jiang and Doyle, 2005; Smith, 2007; Gohm et al., 2008). These jumps dissipate flow energy, which can be related to the decrease of Bernoulli function for each airstream passing through them (Pan and Smith, 1999). Passes or gaps and peaks generate lateral variations in jump intensities (or even their presence/absence) along the mountain lee (coast parallel), yielding the lateral gradient of Bernoulli function, and thus, lateral gradients in PV (Schär and Smith, 1993a,b; Pan and Smith, 1999; Smith et al., 2007). The latter authors study strong LLJs off the mountain gaps, and wakes and hydraulic jumps off the peaks; these, in turn, are related to the PV pairs (banners, e.g. Fig. 3) and Bernoulli function losses.

3. Contemporary advances and questions

Below we briefly review recently recognized mesoscale and turbulence aspects of bora. Through combined overview of measurements and numerical simulations, we concentrate on a few intriguing features such as: bora quasi-periodic pulsations, lee side rotors, secondary effects of the Earth rotation and air–sea interaction. In tackling our goal, we focus more on the last several years of the research progress of the Adriatic bora.

3.1. Mesoscale structures

Some of the first successful 3-D realistic bora simulations using NWP models were performed by Tošić and Lazić (1998), Lazić and Tošić (1998) and Brzović (1999). Brzović (1999) also addressed a secondary Alpine lee cyclogenesis over the Adriatic Sea[3] that is often a precursor of severe bora. Soon after their pioneering work, with overall advances in numerical modelling capabilities, the others continued to model the Adriatic bora with ever refining 3-D models resolution, nesting and assimilation techniques, etc. (e.g. Qian and Giraud, 2000; Klaić et al., 2003; Morelli and Berni, 2003; Belušić and Klaić, 2004, 2006; Cesini et al., 2004; Grubišić, 2004; Ivatek-Šahdan and Tudor, 2004; Gohm and Mayr, 2005a; Ivatek-Šahdan and Ivančan-Picek, 2006; Kraljević and Grisogono, 2006; Pullen et al., 2006). Majority of these studies pertain to real case studies and sensitivity tests, for example, as the one in Fig. 3. Figures similar to Fig. 3 are found in Grubišić (2004) and Jiang and Doyle (2005); thus, it appears that for successful simulations of the NE

[3]Primary Alpine lee cyclogenesis is considered here as the one in the broader region of the gulf of Genoa which is one of the most active mesoscale cyclogenesis regions in the world (Pettersen, 1956; Trigo et al., 1999).

Adriatic bora PV banners pattern, it is sufficient to use horizontal model resolution of about $\Delta x \leq 3$ km. Ivatek-Šahdan and Tudor (2004) used the method of dynamic adaptation (Žagar and Rakovec, 1999) for the improvement of the bora forecast—with success as verified against the data. This is also the operational method at the Croatian Weather Service nowadays. Some of the studies point to the importance of a fine assimilation technique for an advanced bora severity prediction. Without a decent assimilation method, a NWP model's minor displacement of a future synoptic setup between, for instance, the central Europe and Mediterranean may miss the onset, timing or/and severity of bora (e.g. Horvath et al., 2006). Even more, bora might be mistakenly forecasted/replaced by an almost opposite wind, for example, a type of sirocco (local name 'jugo')—all that for a relatively small displacement of the positions of main low- and high-pressure systems.

Before we proceed with bora meso- and microscale aspects, a precautionary note about models is in order. It appears that most of fine mesoscale models simulate the basic bora structures reliably (Grubišić, 2004; Jiang and Doyle, 2005; Belušić et al., 2007; Gohm et al., 2008); however, the details related to small scale features of a few Δx and/or Δz may be doubtful. This firstly comes as a possible warning because of the models' sensitivity to turbulence parametrization, for example, various length-scales deployed in the model, parameters, etc. (e.g. Gohm et al., 2008). Moreover, model turbulence schemes are virtually all made for horizontally homogeneous flow, which becomes almost nonexisting at fine resolutions. Furthermore, numerical diffusion at model low levels could be wrong over steep terrain (Zängl, 2002; Smith et al., 2007). Too much or too little vertical mixing may yield a model thermal bias in the boundary layer, artificial modifications of the LLJ (e.g. Baklanov and Grisogono, 2007; Grisogono et al., 2007; Gohm et al., 2008), etc. These and related questions are not fully solved yet, but progress is being made and much effort is put in improving the details of vigorous orographic flows (e.g. Smith et al., 2007).

The next major advancement in terms of detailed measurements, and after Smith (1987), is the estimation of bora flow PV based on airborne data done by Grubišić (2004). She also verified in situ measurements against the numerical simulation using COAMPS®. The concept of PV is important not only on the synoptic scale but also on mesoscale, especially so in the context of downslope windstorms; it can be related to wave breaking and lee side vortex shading (Schär and Smith, 1993a,b; Schär and Durran, 1997; Grubišić, 2004; Jiang and Doyle, 2005). Gohm and Mayr (2005a,b) also successfully assessed the bora details using airborne observations and meso-γ-scale numerical modelling. An example of bora PV banners is shown in Fig. 3, as simulated by the mesoscale model MM5; a very similar pattern was observed by Grubišić (2004). These studies show that typical PV values for bora are $\sim$10 PVU and that they have a characteristic horizontal scale of 10 to 25 km.

The concept of jets and wakes related to mountain gaps and peaks has been theoretically studied by Pan and Smith (1999). It has been shown that the horizontal spatial distribution of bora maxima and minima along the Adriatic coast depends on the existence of several gaps (passes) in the Dinaric Alps range (Orlić et al., 1994; Zecchetto and Cappa, 2001; Grubišić, 2004; Gohm and Mayr, 2005a; Jiang and Doyle, 2005; Belušić and Klaić, 2006). For stronger bora cases, the dynamics is in accordance with the results of Pan and Smith (1999). The interchanging jets, that is, the LLJ as shooting offshore flows, and wakes also significantly influence the Adriatic circulation (see below).

For weak-to-moderate bora, Gohm and Mayr (2005a,b) confirm the diurnal variation of bora; bora is usually stronger during nighttime, when its shooting flow dominates. During the daytime, bora typically weakens somewhat due to the evolution of a nearly-neutral, sometimes even convective boundary layer over the land. In their simulations without surface friction, the generation of PV is mostly due to buoyancy wave breaking. On the contrary, including this friction, thus simulating a more realistic flow, the PV primary production is flow separation controlled by surface friction.

Even the most recent studies, as that by Gohm et al. (2008) using more advanced observational and computational techniques than did Smith (1987) and Klemp and Durran (1987), consistently prove that severe bora cases are primarily governed by wave breaking. Figure 4 (Gohm et al. 2008; their fig. 10) shows airborne measurements and the corresponding RAMS simulation of a typical bora case on 4 April 2002. Two shooting flows, that is, LLJs, beneath two primary (i.e. low-level) wave breaking regions are displayed.

3.2. *Rotors*

Rotors are vigorous horizontally aligned vortices, associated with lee waves or even hydraulic jumps. It took a long time since Mohorovičić (1889) to reassess lee-side rotor structure associated with bora. Mountain wave induced rotors have been studied quantitatively elsewhere (e.g. Kuettner, 1938; Holmboe and Klieforth, 1957; Doyle and Durran, 2002, 2004; Hertenstein and Kuettner, 2005). Zängl and Hornsteiner (2007) show that strong downslope windstorms may form due to trapped lee waves, which on the other hand create favourable conditions for the appearance of rotors. Therefore, the rotors and severe bora may coexist together (e.g. Belušić et al., 2007; Gohm at al., 2008). The bora rotors are being studied nowadays, using relatively more of modelling than observational approaches (Gohm and Mayr, 2005b), hence implying that a new dedicated field project may appear necessary. Such a campaign should also take into account a unique distribution of the Adriatic islands affecting the occurence and presistence of rotors. For rotors to occur, the no-slip lower boundary condition and vertical shear of the horizontal wind perpendicular to the terrain play essential roles.

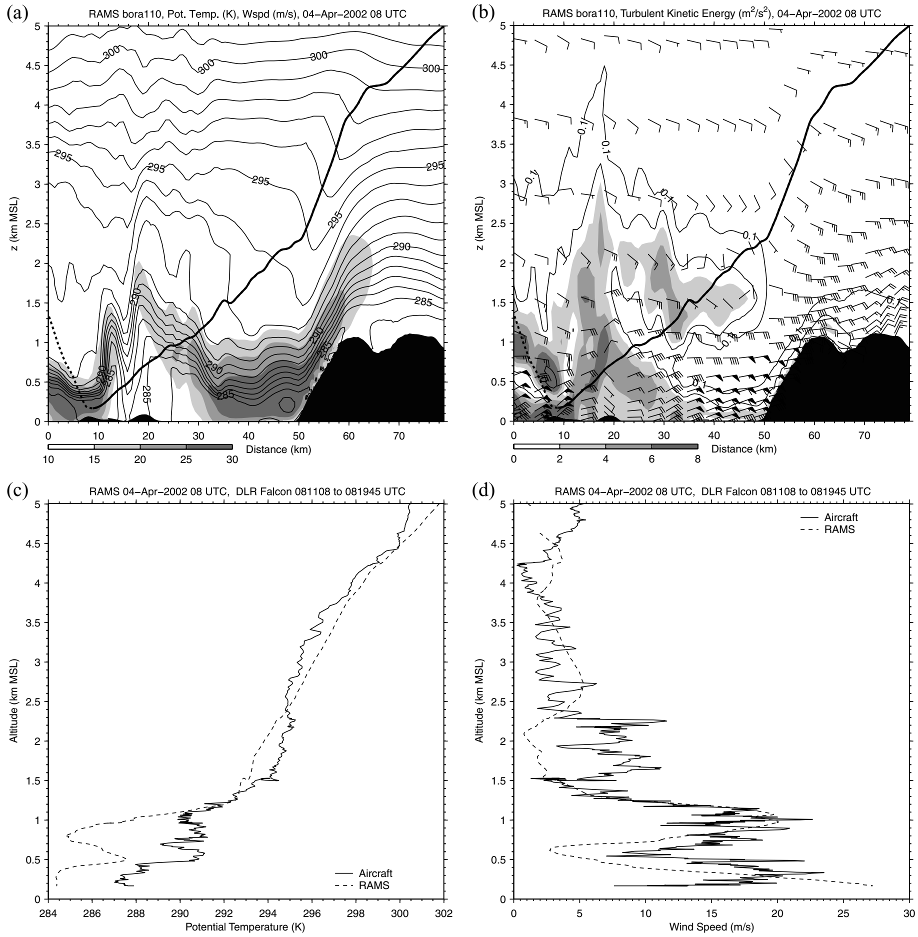

Fig. 4. Vertical transect (a and b) parallel to the Dinaric Alps along northwest to southeast, from the northern tip of Krk island, over Senj town to the northern part of Velebit mountain; (c and d) profile of the atmosphere along a slanted flight path indicated as a thick solid line in (a) and (b) at approximately 08 UTC on 4 April 2002. From Gohm et al. (2008; their fig. 10). Copyright (2008) RMS; reproduced by permission of the Royal Meteorological Society. RAMS reference simulation illustrated as: (a) contour lines of potential temperature with 1 K increments and grey-shaded contours of horizontal wind speed with 5 m s^{-1} increments and (b) grey-shaded contours of TKE with 2 m^2 s^{-2} increments (with black contour lines for 0.1, 1 and 10 m^2 s^{-2}) and wind barbs for the horizontal wind direction and speed. Half barbs, full barbs and triangles denote winds of 2.5, 5 and 25 m s^{-1}, respectively. Observed (solid line, 08:11–08:20 UTC) and simulated (dashed line, 08 UTC) slanted profiles of (c) potential temperature and (d) horizontal wind speed.

The former can yield the boundary-layer separation; the latter substantially enhances the horizontal vortices. The relevant textbooks and most of accessible peer-reviewed literature over the last 60 yr (e.g. Queney, 1948; Scorer and Klieforth, 1959; Yoshino, 1976; Smith 1979b, 2002; Vinnichenko et al., 1980) do not mention, probably the first paper about the lee side rotors, that of Mohorovičić (1889). Details about this peculiarity and more may be found in Grubišić and Orlić (2007).

Vosper (2004) studies inversion effects on the formation of lee waves, lee-wave rotors, low-level hydraulic jumps and the occurrence of wave breaking aloft. Furthermore, he shows the importance of the no-slip lower boundary condition promoting boundary-layer separation under the wave crests, which eventually yields to closed rotor circulations in the lee. His idealized study is in agreement with results about bora rotors as in Belušić et al. (2007). It seems that the presence of islands (promoting both the boundary-layer separation through surface roughness, temperature abrupt changes and vertical downwind shear, $\mathrm{d}U/\mathrm{d}z \gg 0$), more or less aligned with the eastern Adriatic coast, enhances the formation of rotors (e.g. Gohm et al., 2008). The latter authors, using RAMS, found in a bora episode a simultaneous appearance of both hydraulic jumps and rotors but separated now in space (finest mesh with $\Delta x = 267$ m). Figure 5 (their fig. 11) displays a low-level wind field, Fig. 5a, one coast-parallel, Fig. 5b, and two coast-perpendicular transects, Figs. 5c and d, from a fine-scale RAMS simulation. Between 17.5 and 24 km of the horizontal distance in Fig. 5b, there is a wake associated with a wave-induced rotor. This horizontally

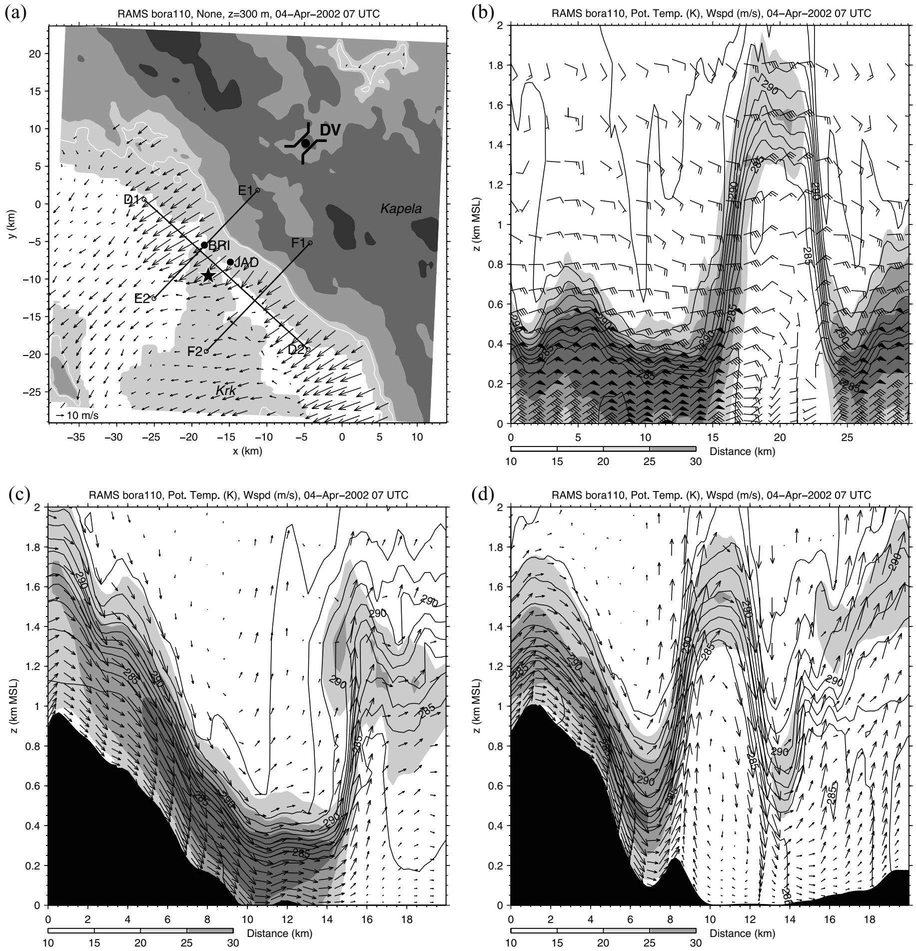

Fig. 5. Flow structure in the vicinity of Rijeka airport (Krk island) NW from Senj, downstream of the mountain gap Delnice Vrata ('DV') at 07 UTC on 4 April 2002, as represented by RAMS, from Gohm et al. (2008; their fig. 11). Copyright (2008) RMS; reproduced by permission of the Royal Meteorological Society. Plan view (a) of horizontal wind vectors at 300 m above mean sea level, the terrain is grey- shaded. Rijeka airport on Krk island is indicated by a star. Vertical transects: (b) parallel to the coastline along the leg D1–D2; (c) perpendicular to the coastline along the leg E1–E2; (d) along F1–F2. Contour lines of potential temperature have 1 K increments, and grey-shaded contours of horizontal wind speed have 5 m s^{-1} increments. In (b), wind barbs for the horizontal wind direction and speed are as described in Fig. 4b. In (c) and (d), wind vectors show the components parallel to the cross-section.

aligned mountain-parallel vortex forms by boundary-layer separation underneath trapped mountain lee waves due to an adverse pressure gradient induced by the first wave crest (Doyle and Durran, 2002). Doyle and Durran (2007) explain that such rotors are not very coherent and relatively laminar structures but, instead, have embedded subrotors (and possibly bursts and sweeps, the authors' assertion). Whereas Fig. 5c shows the lee side shooting flow below the wave breaking, followed up by a hydraulic jump-like transition from strong to week wind speeds, the rotor appears nicely in Fig. 5d, taken more SE than the former transect (see Fig. 5a for the transects). The shooting flow in Fig. 5d does not end with a hydraulic jump, as in, for example, Fig. 5c, but instead with the rotor roughly between 9 and 13 km at this instant. The more vigorous flow, Fig. 5c, is associated with an upwind mountain gap favouring an earlier breakthrough of bora and forming its hydraulic jump. Meantime, Fig. 5d, with its adjacent relatively higher terrain (not shown in Fig. 5d but inferred from e.g. Fig. 5a), promotes a flow separation with the rotor formation and thus, an offshore spatially delayed bora breakthrough. The island of Krk, Fig. 5d, in the right-hand corner, also adds in some ways to promotion of the flow separation and the eventual occurrence of the rotor, but quantitative details are still unknown. Finally, spatial details and transitional behaviour in bora flow are apparently sensitive to turbulence parametrization deployed (Gohm et al., 2008).

3.3. Pulsations

The main property of bora is its gustiness (Mohorovičić, 1889; Yoshino, 1976; Jurčec, 1981; Petkovšek, 1982; Smith, 1987;

Belušić et al., 2006; Grubišić and Orlić, 2007), see Fig. 2. The associated hourly mean wind speeds surpassing 20 m s^{-1} and having gusts up to 50 or even 70 m s^{-1} in the mountain lee areas are common. The maximum hourly gusts are usually approximately twice the mean hourly wind speed (Belušić et al. 2006). Belušić and Klaić (2004) used a mesoscale model to predict the strength of bora gusts, which are also difficult to measure (the fast response instruments can simply break under such tensions and velocity variations); they used an energy based approach. The research on bora gustiness goes back to Yoshino (1976), Petkovšek (1982, 1987) and Rakovec (1987). Data sets presented and analysed by Belušić et al. (2004, 2006) assess fine-scale bora spectrum, namely its turbulence, quasi-periodic pulsations, Fig. 2, and mesoscale severity. Motivated by Petkovšek (1982) and others, who were among the first to analyse bora high-frequency spectrum but only over a relatively short period of time (up to several hours), Belušić et al. (2004, 2006, 2007) explained the multiple appearance and disappearance of quasi-periodic, non-local bora fluctuations using sufficiently long data sets.

The above mentioned 'oscillations' of the bora gusts, that is, the pulsations, represent quasi-periodic contribution to the total gustiness. They appear at periods of $\sim$ 3 to 11 min, Fig. 2. A fuller statistics of these pulsations are given in Belušić et al. (2004, 2006), showing that bora turbulence spectrum during pulsations may be related to its local and non-local (due to pulsations) origin; furthermore, more than a tentative explanation of this phenomenon is given by Belušić et al. (2007). Next we summarize their findings. The model COAMPS® simulated a wintertime bora case with its $\sim$7 min periodicity of the pulsations and the main atmospheric flow structure. The results suggest the Kelvin–Helmholtz instability (KHI) as the most likely pulsating mechanism in the studied case. This instability appears above the bora shooting flow, which is essentially a lee terrain-perpendicular LLJ with its maximum at about (500 $\pm$ 300) m AGL (the shooting flow), and below the wave-breaking region. Figure 6 depicts a downslope propagation of bora pulses (Belušić et al., 2007); this is the modelled counterpart of the pulsations shown in Fig. 2. It has further been shown that decreasing of the local bora flow non-linearity due to enhanced positive vertical wind shear (induced by the passage of the upper tropospheric jet stream) diminishes the primary (i.e. low-level) wave breaking in the lower troposphere. This decrease of non-linearity occurs because of the local *Nlp* increase with the increase of the mean wind speed; instead of the primary wave breaking, large lee waves occurred. Due to reduced vertical shear above the bora jet, KHI is suppressed and hence the related pulsations disappear. On the other hand, at these times, the secondary (i.e. elevated) wave breaking may occur around the tropopause. It seems that the lee-side mountain-wave-induced rotors can appear in the situation when the pulsations are absent (Belušić et al., 2007).

Boundary layers and turbulence in complex terrain are poorly understood even today (Baklanov and Grisogono, 2007; Rotach and Zardi, 2007). Consequently, this affects the bora-related modelling via turbulence parametrization schemes and overall treatment of wave-turbulence interaction (e.g. Smith et al., 2007; Gohm et al., 2008). For instance, the use of Monin–Obukhov length-scale for parametrizing the surface layer, or at least in

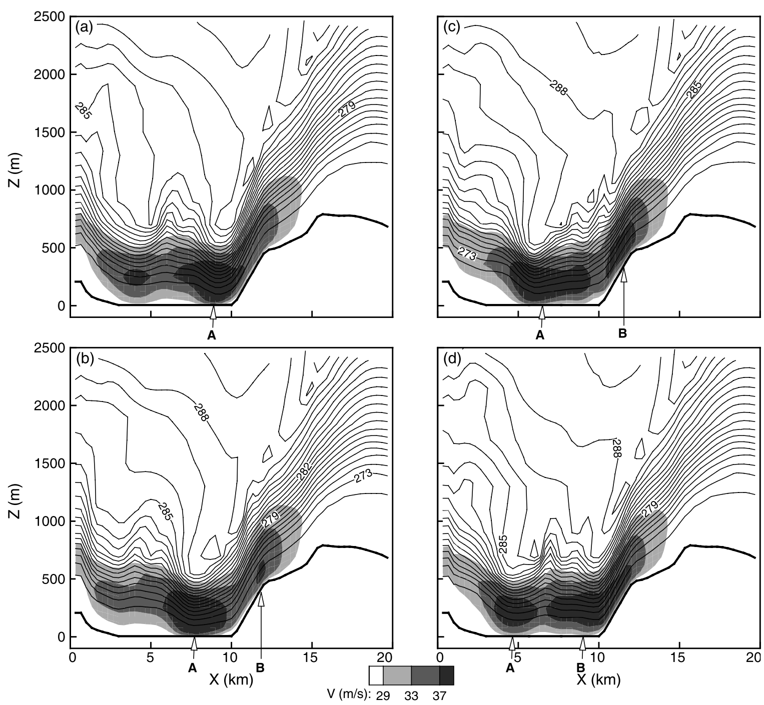

Fig. 6. Pulsations as in Belušić et al. (2007, their fig. 13). Copyright (2007) RMS; reproduced by permission of the Royal Meteorological Society. Wind speed magnitude (shaded above 29 m s^{-1} with 4 m s^{-1} interval) and potential temperature (contours by 1 K) for 8 Dec 2001 at 09 LST and (a) 650, (b) 750, (c) 850 and (d) 950 s; A and B denote individual pulsations. Thick curve represents the underlying orography.

formulating the lower boundary condition in mesoscale models with ever refining resolution, is problematic over complex terrain (e.g. Rotach and Zardi, 2007; Grisogono et al., 2007). These points add up to the lack of knowledge about the upwind bora preconditioning in terms of pre-existing waves and cooled or warmed sloped boundary layers. Guessing from the map in Fig. 1, one expects a more complex upwind preconditioning for bora at the southern Adriatic, say south of $\sim 44°$N. Meantime, the major international projects ALPEX and MAP could not have reached sufficiently far south to observe the southern Adriatic bora. Airborne and remote sensing techniques appear as necessary tools besides fast response near-surface measurements (Smith, 1987, 1991; Belušić et al., 2004, 2006; Grubišić, 2004; Gohm and Mayr, 2005a; Jiang and Doyle, 2005); nonetheless, remote sensing (e.g. wind profilers and radars) has not been fully deployed in bora studies yet.

3.4. *Possible Coriolis effects on bora*

One issue that is barely explored and understood is the effect of Earth rotation on bora flows. Hence, in a sense, this subsection remains quite speculative, but it is still included to shed some light on possible bora explorations in future. This effect can be important for a detailed, lasting bora prediction, related LLJs and calms, not to mention the theoretical relevance. A simple linear analysis (Smith, 1979a; Wippermann, 1981; Grisogono et al., 1993) suggests that the Earth rotation is unimportant for flows over the Dinaric Alps, for example, the mountain of Velebit, at sufficiently low *Nlp* and moderately high Rossby number(s). However, there is a non-linear regime where this rotation becomes relevant (e.g. Ólafsson and Bougeault, 1997; Enger and Grisogono, 1998; Hunt et al., 2001). There is no suitable spatio-temporal data coverage at the Adriatic–Dinaric area to verify this theoretical issue. Nonetheless, often stronger-than-elsewhere bora at the southern Velebit flank, near the bridge of Maslenica, is consistent with the theoretical finding of Grisogono and Enger (2004). They indicate that the Earth rotation might be the explanation for this often observed local bora maximum (aside a possible explanation due to purely local effects). The incoming flow with a principal easterly component senses the preferential low-level pressure on its left-hand side, which is southward; hence, low-level strong bora prefers the mountain's southerly flank. Mesoscale details of such mesoscale flows at large but not infinite Rossby numbers may be found in, for example, Hunt et al. (1997, 2001). The surrounding mountains make significant flow impacts and hinder a simple quantification of Coriolis effects on bora; moreover, the incoming bora flow is, to some extent, preconditioned by upwind mountains (Smith, 1987; Glasnović and Jurčec, 1990). This seems to play an important role when discussing apparent differences between the northern (lesser extent of the upwind mountains) and southern bora cases (Jurčec and Visković, 1994; Ivančan-Picek and Tutiš, 1996); the Coriolis effect there might also affect bora to some notable degree (see e.g. Hunt et al., 1997, 2001). Subtle rotational effects in bora flows could occur due to lasting (wintertime) non-linear interactions, as found in idealized studies (Enger and Grisogono, 1998; Grisogono and Enger, 2004; Kraljević and Grisogono, 2006). This can also be assessed from Ólafsson and Bougeault (1997) and Ólafsson (2000).

Some of rotational effects related to gap flows in the Alps are assessed by Sprenger and Schär (2001). They find that the flow within the gap decouples from the flow aloft, which is driven by the geostrophic south-north pressure gradient to yield a föhn-like flow. Since they considered the Rossby number range corresponding to the Alps, which is about one, it is difficult to extend their study (because the flow is non-linear) to the Dinaric Alps, where the Rossby number can be five or ten times larger. Zängl (2002) shows that the upstream blocking and lower tropospheric wave breaking play essential role in non-linear rotational flow over mountains with gaps. There the pressure difference across the mountain ridge primarily drives the gap flow, which then tends to be decoupled from the flow over the adjacent ridge (Zängl, 2005). This could also be the case at least for some moderate bora cases.

Due to the flow asymmetry related to $Nlp < 1$ and finite Rossby number, the boundary layer structure differs between the northern and southern mountain lee sides. Figure 7 illustrates a possible effect of Coriolis force on a moderate to strong bora in the lower part of the boundary layer. These four idealized simulations are performed using MIUU model with the same setup as in Grisogono and Enger (2004) but now also including a mountain pass, that is, gap (emulating e.g. the effect of Vratnik Pass near Senj, northern flank of Velebit), Figs. 7b and d. Note the lower boundary condition is 'no-slip'. The boundary layer wind is stronger toward left-hand (northern) boundary, Figs. 7c and d, because the wind favours the lower pressure, which in this case appears to the left-hand side of the incoming (geostropically balanced) flow. This is also the main argument of Hunt et al. (2001) and others for the importance of the Coriolis effect, once the mountain length is comparable to the internal Rossby radius of deformation (say $\sim$100 km). By the same token, for the geostrophic flow with an easterly component as bora, the rest be the same as for Fig. 7, the corresponding boundary layer flow around the mountain should accelerate with a component toward south (where the lower pressure lies). Such a vigorous and variable spatio-temporal flow strongly affects the offshore turbulent kinetic energy (its max $\sim$10 J kg^{-1}), humidity distribution, sea surface curl of the stress, etc. Once again, necessary observations to confirm or discard the theoretical expectation that the southern LLJ due to bora at Velebit mountain should be stronger than its northern flank counterpart are mostly lacking. There is no steady-state bora even in this idealized simulation, the flow asymmetry and multiple spatio-temporal scale interactions take over any simplistic interpretation of bora wind and its effects. At least a new modelling study is needed using the

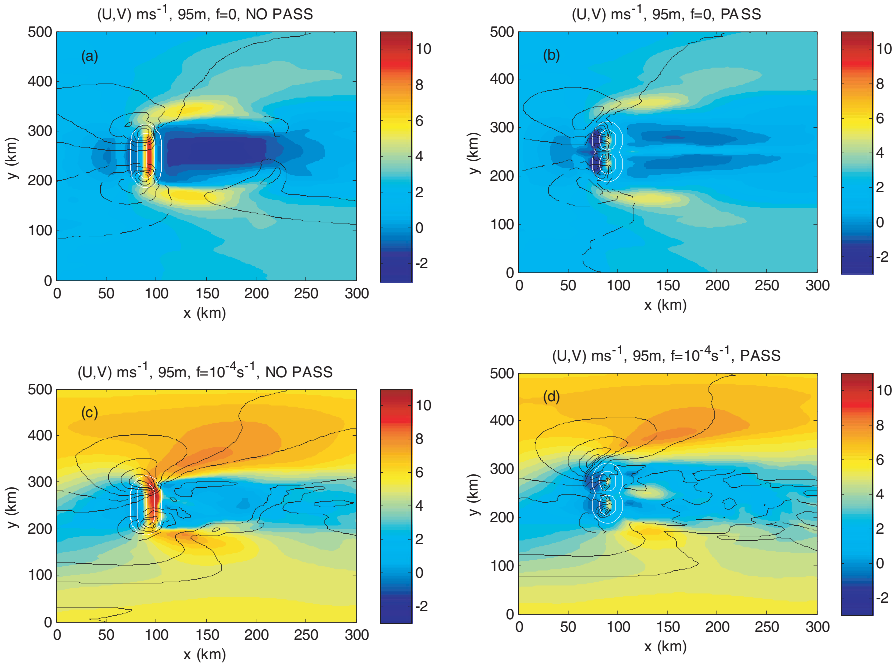

Fig. 7. The U (coloured) and V-component (1 m s^{-1} increment, black, positive solid, negative dashed, 0 suppressed) at 95 m a.g.l. after 20 h; flow is from left- to right-hand side. The terrain is 0.1, 0.5 & 1 km (white). No pass (a and c), with pass (b and d), no Coriolis (a and b), Coriolis parameter $f = 10^{-4}$ s^{-1} (c and d). Simulations based on Grisogono and Enger (2004): constant inflow of 8 m s^{-1}, with no-slip lower boundary condition, non-linearity parameter $Nlp = 0.6$, mountain = 100 km × 20 km × 1 km, pass down to ~ 400 m (b and d). Rossby number along the flow, $Ro = 7.6$ (c and d) or ∞ (a and b). The flow is highly asymmetric due to orographic wave breaking in the lee and presence of rotation.

realistic orography for airflows with and without Coriolis effects and justified model initializations.

3.5. *Air–sea interaction*

Bora and the Adriatic Sea are intimately related (Mohorovičić, 1889; Orlić et al., 1994; Enger and Grisogono, 1998; Brzović, 1999; Beg Paklar et al., 2001, 2005; Pullen et al., 2003, 2006, 2007; Kuzmić et al., 2006; Dorman et al., 2007; Grubišić and Orlić, 2007). This interaction, with timescales of a few days or even less, goes primarily via wind-curl but also divergence driven sea currents, sea surface temperature (SST) feedback and the sea roughness variations. Orlić et al. (1994) explain that the Adriatic Sea shows quite a complicated response to both bora and sirocco wind forcing; it is especially so for bora conditions (Orlić et al., 2007). The response to bora often consists of a few gyres in the near-surface currents, depending where the strongest bora offshore jets occur (i.e. the remnants of the shooting flows), and strongly correlated SST perturbations. Figure 8 shows simulated bora induced gyres of sea surface currents in the northern Adriatic Sea (Pullen et al., 2007). The state of the sea also largely affects the bora evolution and not solely the opposite (i.e. that only would bora force the sea).

Enger and Grisogono (1998), in a 2-D study of SST effects on bora flows, explained that the larger SST with respect to that of the land yields the greater bora fetch over the lee-side sea because the relatively warm SST locally reduces N and hence, it prolongs the lee side flow supercriticality postponing the hydraulic jump. Climatologically speaking, this pertains to wintertime and thus more vigorous bora, and vice versa; the summertime relatively cooler SST, with respect to the warm land temperature, relates to relatively weaker overall bora effects. Moreover, they showed that the state of the coastal boundary layer can sometimes have the same role as a part of the synoptic setup for bora evolution. As the incoming geostrophically balanced wind has a lower pressure to its left-hand side, a similar lower pressure can be generated by a suitably positioned warmer marine boundary layer, thus generating a similar effect as one of the incoming synoptic wind components. Any kind of incoming flow yielding $1/4 < Nlp < 1$ followed by relatively warm sea will produce severe bora conditions. Cesini et al. (2004), Kraljević and Grisogono (2006) and Pullen et al. (2006) extended that work in 3-D domain. The former two confirmed the first findings about the SST effects on bora; of course, the previous 2-D simulations exaggerated the bora front offshore propagation and missed certain intriguing 3-D non-stationary effects on the bora front (in idealized conditions). The latter study, applying a two-way coupled air-sea model, studied bora air-sea interaction more completely. Their study finds out that the upward heat flux is attenuated by 20% compared with that in one-way coupled simulation; two-way coupled sea surface heat fluxes showed in overall more spatial structure. They showed in quite a realistic way that often the

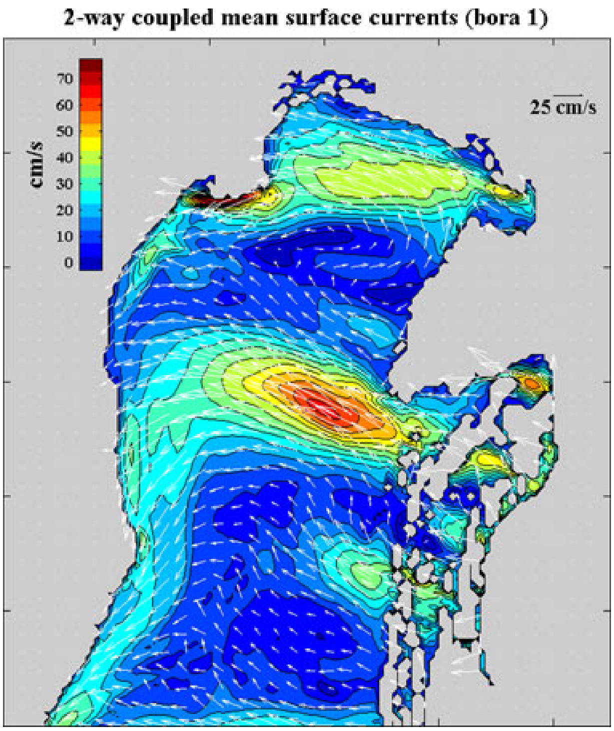

Fig. 8. Bora induced gyre in the northern Adriatic Sea (the figure is rotated, see, for example, Fig. 1 for geographic references). Taken from Pullen et al. (2007, their fig. 8a). Copyright (2007) AGU; reproduced by permission of American Geophysical Union. The bora flows mainly from right- (north-eastern Adriatic) to left-hand side. Shown are ocean surface currents, both in contours and vectors. These mean surface currents correspond to the bora episode from 1400 UTC 31 January to 0600 UTC 2 February 2003.

sea moderates the overall bora effects, say by up to ∼20% in general, that is, in terms of near surface wind and temperature variations (qualitatively revealed by comparing their results to those by Grubišić, 2004; Kraljević and Grisogono, 2006). Pullen et al. (2006, 2007) show in particular, by comparing to both in situ and remotely sensed observations, how important it is to deploy the two-way coupled model system in studying the offshore prospect of bora. For example, they identify a spatially complex SST field after a bora cooling event that corresponds faithfully to the related advanced observations. Hence, this implies that the detailed SST evolution is a key issue in the bora air-sea exchange processes.

4. Concluding remarks

Recent progress and advances in the research of bora severe lee-side windstorm are assessed. The study relates to meso- and microscale bora characteristics analysed during the last few decades. Typical results from fast-response sensors and overall bora observations are briefly described in addition to the results of a few mesoscale numerical models.

Bora is a prime example of a gusty downslope windstorm. The 'classic' strong to severe bora blows at the eastern Adriatic coast with hourly wind speeds surpassing 20 m s^{-1}, whereas gusts extend up to 50 or even 70 m s^{-1} (reaching hurricane speeds e.g. Belušić et al., 2007). These strong near-surface winds are only the surface manifestation of the bora shooting flow, occurring in the lowest troposphere that is usually up to 1-km deep and situated below the primary wave breaking region. Bora is primarily governed by mountain wave overturning and eventual breaking (Smith, 1987; Klemp and Durran, 1987; Jiang and Doyle, 2005; Belušić et al., 2007; Gohm et al., 2008). The progress of bora related 3-D processes, as well as other important effects such as air–sea interaction, pulsations, rotors, etc. during the last ∼ 10 to 20 yr has been quantitatively, or at least qualitatively, addressed.

Future research addressing bora flows should deploy more remote sensing instruments to analyse the onset, details and transient features of bora wave breaking, in addition to the propagation of the substructures down toward the surface (e.g. internal boundary layers). Weak-to-moderate bora cases should be better integrated in such studies, thus assessing the possible importance and interactions with katabatic processes, non-hydrostatic, radiative and moist effects on the flow evolution. As stated, bora pulsations, rotors, lee-side flow separations, eventual Coriolis effects and air–sea interaction should remain in the core of future bora-related research projects. Moreover, the role of the lee-side islands (e.g. Krk, Rab, Pag, etc.) is still not investigated systematically. It is not clear enough how to tackle the details of bora upwind state and the role of the inhomogeneous boundary layer preconditioning the bora incoming flow; moreover, the Dinaric Alps may scale with the internal Rossby radius of deformation. This also yields us toward possible Coriolis effects on bora. A more thorough and systematic analysis of Coriolis effects on long-lasting bora is still to be done, as it is not straightforward to extend the related idealized studies on real cases. At the same time, bora air–sea interaction projects have been already successful and continue to produce relevant results (e.g. Dorman et al., 2007).

Future climate scenarios are still of inadequate resolution today to predict appropriate *Nlp* and Rossby number ranges to estimate future changes in bora severity, duration, frequency of occurrence and seasonal variability, as inferred from, for example, Bengtsson et al. (2006). These estimates demand air–sea coupled models with the finest horizontal resolution of a few kilometres or better. Additionally, even with a relatively coarse resolution used, there are some preliminary indications for a future abatement of bora due to eventual changes in synoptic activity over the broader Adriatic area (Pasarić and Orlić, 2004).

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