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STRONG BORA WIND – RISK FACTOR IN TRAFFIC

SUMMARY

This paper presents a survey of strong bora wind. Bora wind of extreme severity, which may blow along the entire Adriatic coast, usually causes a lot of damage to the electrical power network and a complete road and sea traffic disruption. Therefore, there is a growing need for introducing the bora risk factor in traffic planning.

1. INTRODUCTION

Strong, gusty downslope winds are observed in many mountainous regions of the world. One of the most famous *local winds* is the bora (*bura*) - a severe north-easterly downslope wind along the eastern Adriatic coast.

Although the research (Bajić, 1988, 1992; Ivančan-Picek and Vučetić, 1990; Jurčec, 1981, 1988; Tutiš, 1988, Vučetić, 1985) shows that bora can occur under a wide range of conditions, however, one condition is necessary: there must be a supply of low level cold air. Therefore, we define an *upstream bora layer* as a low-level cold airflow usually capped with an inversion, or as the NE "bora flow" above which wind may or may not change its direction. The upstream bora layer characteristics may greatly differ from case to case as a consequence of the deformable frontal system and the baroclinic structure of the lower troposphere over the region. Wind reversal or inversion formation is usually observed at the bora onset and its developing stage, whereas the decaying period is mostly marked by a lowering of temperature inversion (Glasnović and Jurčec, 1990).

The recent major stride in our knowledge of the bora phenomenon has been made possible by the data set collected during the field experiment in ALPEX SOP with broadened surface and upper air measurements, and particularly by first aerial observations of this phenomenon (Smith, 1987). The theoretical results obtained by Smith (1985) have succeeded in *changing the traditional view of the bora* as a "fall wind" by suggesting that some cases of severe bora might have a hydraulic character. The results of the ALPEX bora analyses mostly coincide with the assumptions of the hydraulic theory (Smith,1987; Bajić,1991). The major benefit of the ALPEX bora studies, in addition to aircraft measurements, is an upper air data set with four radio-sounding stations working at short-time intervals of 3 hours. The major deficiency of these studies is a lack of typical severe bora cases usually defined by the mean hourly wind speed greater than 17 m/s with gusts exceeding 30 m/s, which commonly occur during severe winter conditions. However, most bora research considers the appearance of the severe bora only in the northern Adriatic and very few in the southern Adriatic (where the bora layer is not so well defined on the windward side and the data coverage is not satisfactory).

2. MULTISCALE NATURE OF THE BORA WIND

Thorough comparisons of observational analyses of the northern Adriatic bora and the southern Adriatic bora cases reveal the multiscale nature of bora wind (Jurčec, 1989): although the bora speed and direction are greatly influenced by topographic shape (so mountain and coastal circulation are clearly responsible for a daily variation of wind speed and direction during the bora period), the bora onset, its longevity and severity are closely related to larger mesoscale features, in particular those resulting from the interaction processes of synoptic scale flow with the Alpine massif.

It is well known that the atmosphere is a continuous medium, but there are always more or less recognisable structures present with characteristic dimensions in time and space (like cyclones, anticyclones and fronts). Therefore, the classification of scales of atmospheric motion suggested by Orlanski (1975) was used: microscale is less than 2km, mesoscale is between 2 and 2000 km, and macroscale is greater than 2000 km. There are also subdivisions of scales, e.g. meso-gamma (2 - 20 km), meso-beta (20 - 200 km), meso-alpha (200 - 2000 km).

2.1 Macroscale structure of the bora wind

From macroscale point of view, there are three general types of the bora wind:

1. anticyclonic bora
2. cyclonic bora
3. frontal bora

Anticyclonic bora is a consequence of a cold air-stream in front part of a European anticyclone (Fig.1). The centre of an anticyclone (area of higher atmospheric pressure) in this case is situated north or west of the bora region.

Cyclonic bora (Fig.2) is a consequence of drawing out the air from inland into the Adriatic basin by a Mediterranean cyclone (area of lower atmospheric pressure). For example, a well known Genoa cyclone

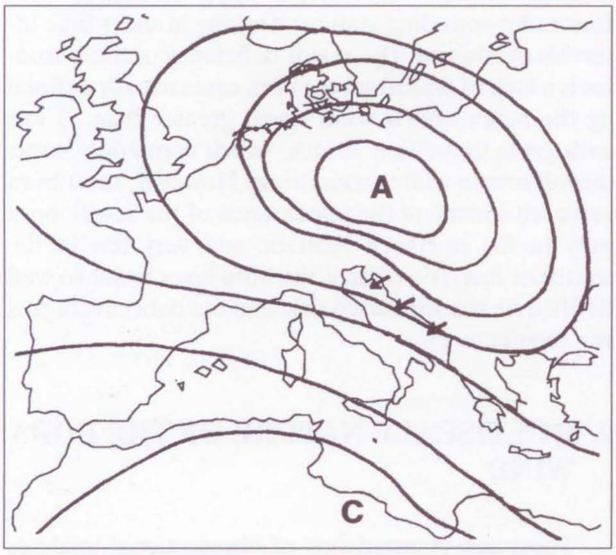

Figure 1 - Schematic representation of surface pressure field in the case of anticyclonic bora

is usually responsible for the northern Adriatic bora of the cyclonic type. However, the cyclonic activity in the eastern Mediterranean and over the Balkans influences the bora structure and behaviour more in the southern Adriatic (Dalmatia) than in the northern Adriatic. In the case of the Adriatic cyclone, jugo blows in the front and bora in the rear of this cyclone. Strong Adriatic cyclones frequently become stationary when reaching the southern Adriatic and extend throughout the troposphere.

Frontal bora (Fig. 3) is caused by a cold air outbreak following the cold front. It is usually rather brief, although some of the most severe cases belong to the frontal type.

So, in relation to synoptic developments, severe bora is always expected as a result of strong cold airflow from inland over the Dinaric Alps into the Adriatic basin. It must be emphasised, that strong bora rarely appears along the entire Adriatic coast simultaneously - in most cases it starts at the northern Adriatic coast and then gradually (if synoptic development permits) spreads southwards, while the NE wind at the northern Adriatic usually weakens. Higher rates of frequency and persistence of the northern Adriatic bora are caused by several factors - e.g. different position relative to the main synoptic systems. Usually, while the bora blows in the northern Adriatic, the jugo (S-SE) wind blows in the middle and southern Adriatic.

According to surface manifestations, the essential difference between the northern and southern Adriatic bora is not in the intensity of maximum wind speed, but in the frequency and persistence.

The statistical analyses (Bajić, 1989; Vučetić, 1991) in the 30-year period of observation (1958-1987) show that severe bora with maximum gusts 40 m/s may ap-

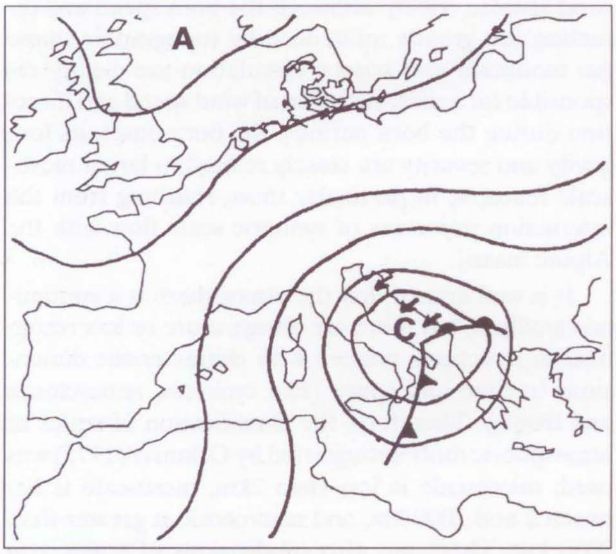

Figure 2 - Schematic representation of surface pressure field in the case of cyclonic bora

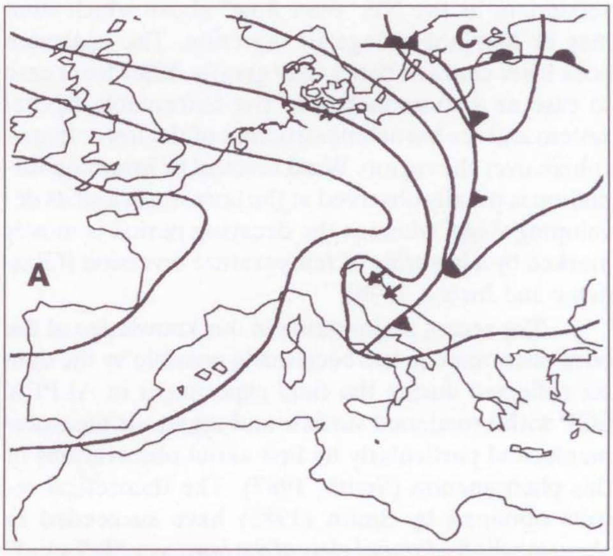

Figure 3 - Schematic representation of surface pressure field in the case of frontal bora

pear along the entire Adriatic coast, but its duration and frequency decrease from the north to the south. Due to complex orography of our coastal area, the strongest and most frequent bora is found in the region of Senj (Luksić, 1975) and Split (Makjanić, 1978). From the statistical survey for 1987-1993 (Brzović and Benković, 1994) it appears that during this period bora was even stronger in the southern than in the northern Adriatic.

2.2 Mesoscale structure of the bora wind

On mesoscale, the severe bora wind is related to the cold airflow in the lower troposphere, upstream blocking, splitting and flowing over the orographic obstacle. Defining *critical level* either as the level of strong temperature inversion or as the level of flow reversal, the *upstream conditions suitable for bora onset* can be divided into two main groups:

1) unidirectional northern flow throughout the troposphere (the tropopause being the capping critical layer)
2) shallow low level bora flow below a critical level (usually at some height in the lower troposphere).

Simultaneous isentropic analyses of atmospheric motion give very realistic 3D picture of airflow. It has been shown that in the lower troposphere during the bora periods there is a pronounced downward NW-SE motion over Europe. Concerning hydraulic character of the atmospheric motion, such inclination of air trajectories indicate strong acceleration of atmospheric motion upstream of the Dinaric Alps.

Consequently, many case studies of the bora events, particularly during the Alpine experiment (ALPEX, March-April 1982) indicate the phenomenon of *low-level jet stream* (LLJ) in connection to the bora flow (also observed in many other mountain regions around the world). A jet is a region of relatively strong wind that is concentrated into a narrow, quasi-horizontal or horizontal stream. The criteria that satisfy the conditions "relatively strong" and "narrow" are subjective for low-level jet streams (below 5 km height). It seems that the LLJ associated with the Adriatic bora flow, undergoes a marked diurnal variation in strength - it is usually stronger at night and weaker during the day (the same variation follows the surface bora wind).

It is well known that the wavelength of orography strongly influences the airflow. Therefore, we analysed the characteristic wavelengths of mountains and mountain chains belonging to the eastern part of the Alps and the Dinaric Alps. The results show that the dominant wavelengths of orography have the strongest impact on atmospheric disturbances in the lower part of the meso-beta scale (Tutiš, 1995) Recent numerical experiments with and without orography (Tafferner,1994; Brzović and Jurčec, 1996) confirmed significant influence of the Dinaric Alps on the lower mesoscale.

A well known feature of atmospheric flow over orography is also the asymmetry of the surface pressure field with high pressure upstream on the mountain and low pressure on the lee side. Therefore, mesoscale analyses show development of high - low pressure couplets (or dipoles) across the Dinaric Alps (Tutiš, 1995). The orographically induced high-low pressure couplet causes strong pressure gradient over the mountainous area. In fact, this pressure gradient implies that the atmosphere tends to push the mountain downstream, phenomenon called the *surface pressure drag*. According to the Newton's third law, the mountain exerts an opposite force on the flow directed upstream, the *mountain drag*. It has to be emphasised that in such situations a surface pressure drag acts as a mechanism of an atmospheric momentum *sink* on synoptic and global scale, but an atmospheric momentum *source* on lower meso-beta and meso-gamma scale.

Investigation of microbarographic measurements during ALPEX SOP and calculation of the pressure drag (Tutiš and Ivančan-Picek, 1991) showed that the pressure drag maxima for the Dinaric Alps are always related to the bora periods. It appears that the bora strength and the pressure drag are strong functions of height and strength of upstream bora layer. Furthermore, the drag value magnitudes indicate that during these events there was a major sink of the large scale atmospheric momentum over the Dinaric Alpine region, even comparable to the larger Alpine region. The weaker downslope winds in time-dependent flows are consistent with reduced drag, since they are associated with smaller pressure differences across the mountain.

Thorough investigation shows that on the mesoscale, the *bora in the northern Adriatic* is mostly caused by the air coming, in fact, from the NW, going around the Alps and therefore gaining NE direction upwind of the Dinaric Alps (Tutiš, 1995). Also, the orographic pressure dipole on the mesoscale can be clearly recognised as a key phenomenon for the organisation and intensification of the local bora wind.

However, studies of *southern Adriatic bora* (Vučetić, 1993; Jurčec and Visković, 1994; Ivančan-Picek and Tutiš, 1995) emphasise large differences between bora structure and mechanism in northern and southern Adriatic.

Jurčec and Visković (1994) selected fifteen severe storms in Split (Dalmatia) during the period January 1980 to January 1983. Several facts proved to be important for the severe southern Adriatic bora:

- all bora cases occur in winter months (December to March)

- severe bora periods in most cases do not last longer than 8 hours
- gusts of the wind speed above 30 m/s, with the absolute maximum of 45 m/s are comparable with the northern Adriatic bora
- the mean surface pressure distribution (Fig.1) and 500 hPa geopotential height show a mesoscale cyclone over the southern Adriatic.

Some observations of windward conditions during southern Adriatic bora indicate the flow splitting and low-tropospheric divergence over the Pannonian plain (Vučetić, 1993) and much thicker upstream bora layer compared to the northern Adriatic cases.

Weak or moderate bora is often confused with *burin*. Burin is also a local wind blowing from the NE quadrant along the coast, but is generically different from bora, and in many ways it much more similar or equivalent to the nocturnal land breeze flow.

Poje (1995) examined the statistical differences between bora and burin and concluded the following:

1. burin often starts in the evening, blowing until morning hours and vanishing around the midday, while the onset of bora depends on general synoptic situation
2. at the onset of bora, the average temperature drop is significantly larger than in the case of burin
3. relative humidity drop is also significant in bora case
4. bora onset is characterised by a sudden increase of the wind speed and velocities are generally higher than in the burin case

2.3. Microscale structure of the bora wind

Investigation of severe gusty winds throughout the world showed significant periodicity of the wind energy peaks (maximum wind energy is reached during gusts).The most well known periods found are 20 to 30 sec, 4 to 5 min and 20 to 30 minutes (only peaks under 1 hour are considered here). To calculate these values, special microbarographic and anemographic measurements should be conducted.

As noticed in the introduction, one of characteristics of the bora wind is gustiness. The gustiness is caused by an internal structure of the bora flow (e.g., one component is highly turbulent surface flow).

Special measurements of the northern Adriatic bora flow were conducted during the ALPEX experiment (surface and aerial observations, Smith, 1987). Results showed an additional region of pronounced turbulence at some height immediately in the lee of the Velebit (the so-called "dead region" where horizontal wind speed decreases).

Such experimental insight in the internal structure of the northern Adriatic bora flow confirmed proposed theoretical hydraulic model (Smith, 1985) and resulted in the first realistic conceptual model of the bora flow , as illustrated in Fig. 4 (where region A represents a region of airflow acceleration, region B is the so-called "dead region" where horizontal wind decreases but severe turbulence is present and region C is surface bora flow in the lee).

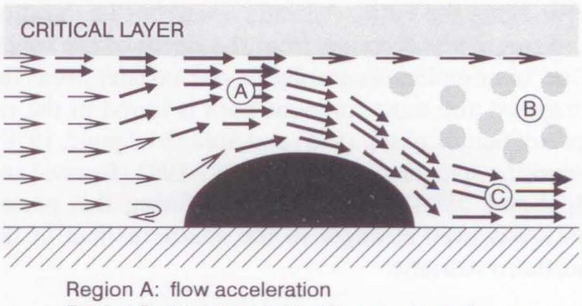

Figure 4 - Conceptual model of two dimensional hydraulic bora flow

The conceptual model of the southern Adriatic bora is more complicated and cannot be approximated by a two-dimensional model. Generally speaking, it involves flow convergence and upward motion on the windward side and usually a wave breaking over the Dinaric Alps, involving motions from much broader scale than bora on the northern Adriatic.

3. CONCLUSION

The aim of this work is to present the knowledge about one of the most famous local winds – bora (*bura*). Bora is strong, gusty, north-easterly downslope wind along the eastern Adriatic coast. The results presented in this paper have substantial implications for the diagnosis and prediction of the bora onset and severity. Knowledge of the mesoscale pressure patterns also increases the forecasting skill for surface winds in the region and improves large-scale numerical models.

Although recent bora investigation showed essential differences between bora behaviour in the northern and southern Adriatic, investigation of all severe bora cases reveal the multiscale nature of bora wind: the bora onset, its longevity and severity are closely related to larger mesoscale features, in particular those resulting from the interaction processes of synoptic scale flow with the Alpine massif and bora speed and direction are greatly influenced by local topographic shape. So, when discussing severe bora wind, we have to account that such windstorms are mostly subsynoptic features, strongly influenced by local processes and orography and are, therefore, very difficult to study by regular synoptic network.

SAŽETAK

OLUJNA BURA – OPASNOST U PROMETU

U ovom radu je pregled istraživanja o olujnoj buri. Olujna i orkanska bura može puhati duž cijele obale i obično izaziva velika oštećenja u elektroenergetskoj mreži te potpun prekid pomorskog, cestovnog i zračnog prometa. Stoga, podaci o buri - bilo klimatološki ili sinoptički - imaju važnu ulogu u planiranju prometa duž jadranske obale.

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