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Main bora gusts – a model explanation

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In contrast to the known models of bora wind, originating from the idea of rather uniform hydraulic flow, the basis of this physical model explanation are observed gust characteristics of bora. The essence of this model explanation is the fact, that bora is primarily a very gusty wind, and the idea that main gusts are not a consequence of turbulence in a general flow, but of cylinders of cold air rolling down the slope on the warm side of the ridge. Main rolls together with the turbulence and partly sliding of cold air develop a general flow with observed bora characteristics.

Glavni sunki burje – modelska razlaga

Za razliko od znanih modelov burje, ki izhajajo iz postavke o dokaj enotnem hidravličnem toku, so osnove te razlage s fizikalnim modelom, opazovane značilnosti burje. Bistvo te modelske razlage je dejstvo, da je burja predvsem zelo sunkovit veter in ideja, da glavni sunki burje niso posledica turbulence v splošnem toku, ampak valjev hladnega zraka, ki se vale po pobočju navzdol na toplejši strani grebena. Glavni valji skupaj s turbulenco in delnim drsenjem hladnega zraka ustvarjajo tok z opazovanimi značilnostmi burje.

1. Introduction

It is known that bora is a relatively cold, dry and very gusty wind of rather constant average direction. Bora is to be found on various appropriate topographic regions but is mostly known from the NE coast of the Adriatic. Bora is not known for its average speed (which is usually not extremly high), but for unexpected violent gusts which exceed by a factor of three or more the average velocities. The gusts are the factor that make bora hazardous to all types of traffic and structures and also influences vegetation and architecture giving its region a typical appearance (e. g. Yoshino, 1976).

Due to mentioned effects, many investigators have researched bora. Many of its characteristics – mainly climatic, have been known for a long time. Some special characteristics in microscale of time and space, are known only recently, however, Many models of bora wind have been made as well (Arakawa, 1976, Yoshino, 1976, Makjanić, 1970, Ivančan-Picek, 1984, Økland, 1984, Hoinka, 1985), but none of them includes or can explain bora's most essential characteristic – its outstanding gustiness.

Many new facts and findings, especially about the bora gusts, led us to start just with the gusts, and create a particular model. This can be combined with some others, giving a basis for a complete numerical model for diagnosis and forecasting of bora, including its violent gusts.

2. Important observed facts and findings to date

Let us first briefly consider the main facts of bora characteristics, recognised by many observations, measurements, and studies, as well as by some experiences of fishermen in the bora region. The latter were collected by the author and by Watanabe (1976).

For a convenient presentation of facts and model, the broader region of formation and influence of bora is devided in three domains (I, II and III – Fig. 1). In short the following can be said about bora:

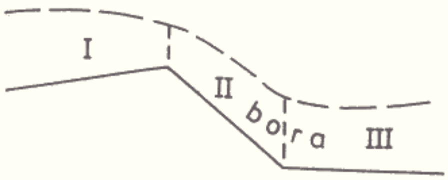

Figure 1. Schematic crossection of the broader bora region.

2.1. Bora wind develops after the invasion of cold air in lower layers of domain I, while the atmosphere on the opposite sea-side of the ridge (domains II and III) is much warmer (e.g. Paradiž, 1957, Yoshino, 1976, Jurčec, 1984). The pressure gradient at the surface is very strong due to the ridge separating the air of different densities, but has usually only a small influence on the air flow over the ridge. The winds in cold air are weak or moderate, on the coastal side, however, a violent bora dominates.

2.2. On the boundary between the lower cold and the upper warm air in domain I there is a stable air layer of temperature inversion. Internal gravity waves created due to broader topography are well seen on the upper layer of cloudy or foggy cold air under the inversion, if observed from the neighbouring peaks or in aerial or satellite pictures (Petkovšek, 1982, Kennedy, 1982, Smith, 1984).

2.3. The amplitude, wave length and phase speed of these waves depend on many external and internal factors. Special analyses of such waves (e.g. Vrhovec, 1982) show, however, that for the wave lengths greater than 3 km, the phase speeds are rather constant.

2.4. The typical height of the cold air in domain I in developed bora is between 2 and 3 km, but considerably lower in domains II and III – by about a half (Poje, 1962, Smith, 1982, Rakovec and Petkovšek, 1983, Jurčec, 1984). Therefore the horizontal temperature gradient is of the order of a degree per kilometer.

2.5. The direction of bora on the Adriatic coast is from the NE quadrant but the winds in the warm air above the bora are often perpendicular or even opposite (Poje, 1962, Vučetić, 1984), maintaining a strong temperature difference.

2.6. There exist practically no surface measurements in domain II, but there are a few aerial pictures or measurements from the heights above the bora layer only (Smith, 1982, Kennedy, 1982).

2.7. In domain III bora usually starts with separate gusts but in less than 20 minutes a strong gusty wind in the lower layers develops – Figs. 2 and 3.

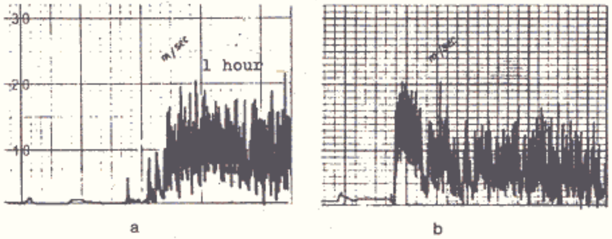

Figure 2. Registration of two bora beginnings with classical anemograph: a) typical, b) extremly sudden case.

2.8. Typical average wind speeds of bora at the surface are between 10 and 15m/s, but in gusts they can be 3.5 times greater and exceed 50 m/s (Koračin, 1984, Yoshino, 1976). The vertical wind profiles show a maximum at the height of about 1 km (Poje, 1962, Jurčec, 1984).

2.9. Typical bora duration on the Northern Adriatic is one day (but it can be 12 days). Therefore in the period of a few hours (except at the beginning), bora can be treated as a quasistationary, but always very gusty wind (Petkovšek and Paradiž, 1976, Yoshino, 1976, Lukšić, 1975, Koračin, 1982).

2.10. An essential characteristic of bora is its strong gustiness. Low time-lag instrument registration even show calms among the gusts – Fig. 3. On the sea surface often a belt of outstanding white-caps can be seen, directed parallel to the ridge.

2.11. Spectral analyses of bora wind speed for the periods between 0.5 and 20 minutes show characteristic increase of energy, and peaks in periods between 3 and 11 minutes, often with doubling of periods (Petkovšek and Rakovec, 1983, Koračin, 1982, Petkovšek, 1984). In the known Van der Hoven's spectrum of wind in the planetary boundary layer in the periods of 2 minutes, and more at the side of the gap, strong decrease of energy can be found (Pančev, 1976), in bora spectrum, however, here begins strong increase of energy. In the experiences of fishermen, the main bora gusts repeat every 3 to 4 minutes (Watanabe, 1976).

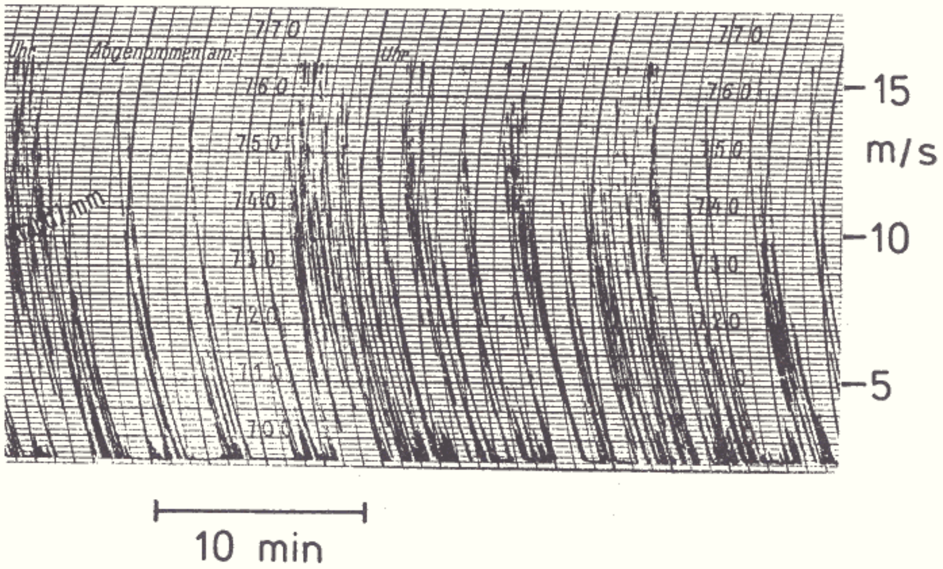

Figure 3. A part of a registration of bora with the instrument of very small time lag (few seconds), 7 km from the foothill.

2.12. A special analysis of gusts and gaps on three speed levels, gave a simple and significant registration pattern of bora – Fig. 4 (Petkovšek, 1984). It is obvious from it, that the gusts usually start rather suddenly, then weaken and are followed by the gaps or weak wind periods. In the treated cases the gaps lasted about a third of the whole period. Similar patterns can be seen on actual registrations – Figs. 2 and 3.

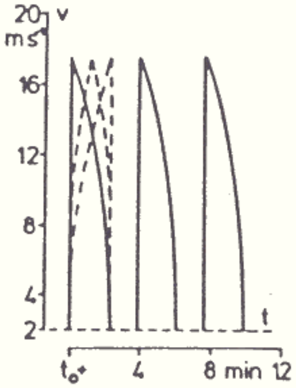

Figure 4. Average bora pattern – gusts and gaps, obtained from a 5-hour registration of type in Fig. 3.

2.13. The strong bora gusts at the sea surface (that raise a plume of spray) travel only a little faster than the average speed and show a distinctive lifting of the spray on the frontal part (Petkovšek, 1984) – Fig. 5.

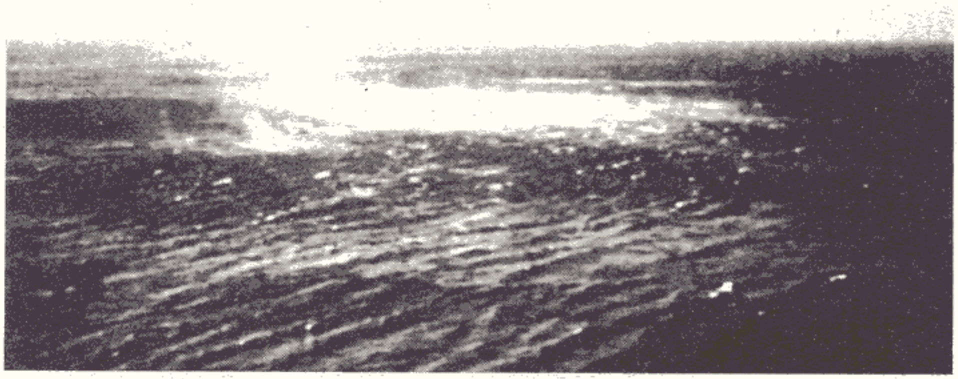

Figure 5. Photo of sea-spray plume in a moderate bora.

3. A simplified basic model

On the basis of the presented recognitions of bora characteristics, an unconventional simple physical model of bora is presented, mainly graphycally in a two-dimensional form. It is valid for a quasistationary state of a developed system in a vertical crossection, perpendicular to the ridge and parallel with the bora. It is supported by partial calculations, and should give a basis for a complete consistent numerical model, which should be a tool for nowcasting of main bora gusts or their periods.

3.1. The waves before the ridge

In domain I internal gravity waves are created on the upper layer of invading cold air. In general they have different characteristics and are usually combined or superimposed. In this presentation they will be simplified, and waving in paralel with the ridge (Fig. 6, left).

According to Caughey (1979) the highest frequency of the internal gravity waves is the Brunt–Väisälä:

$$N = (g/\Theta \cdot \partial\Theta/\partial z)^{1/2} \qquad (1)$$

but it can of course also be lower. Typical values for N in the conditions prevailing in domain I are about 10^{-2} per second, or period above one minute. According to the recognitions of the previous chapter, a 4-minute period will be used in this presentation.

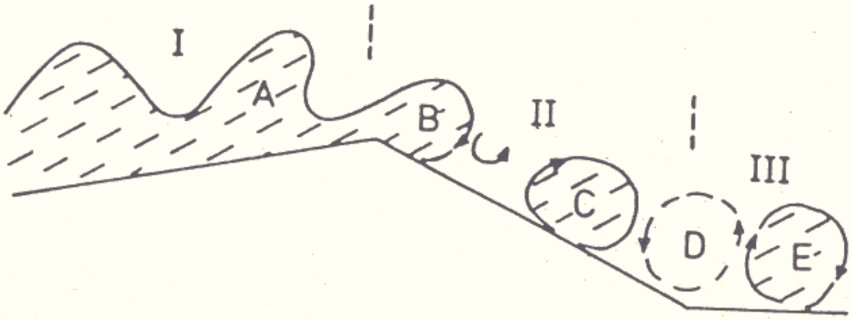

Figure 6. Scheme of internal waves on the upper boundary of cold air before the ridge, and rolling of cold air cylinders on the sea side.

Before and above the ridge, where the height of the cold air is slowly diminished, hydraulic effects may be important and Froude number, given e.g. by

$$F = v / h'N \tag{2}$$

may be relevant, having inland low values (F = 0.3) and increasing toward the ridge (Smith, 1982). Downward the ridge, however, the observed gustiness could hardly be explained with the hydraulic flow.

In a typical case of a relatively thin layer of cold air, becoming even more shallow toward the ridge, there is an example of the waves at the beach or at the undersurface ridge, where increasing amplitude and increasing incident wave-steepness is being created. Like a plunging breaker (Mitsuyasu, 1982) the cold air is overthrown on the warmer sea-side of the ridge -Fig. 6,B.

3.2. Events at the slope

The considerable amount of cold air reaching the ridge with the increasing gravity wave has a moderate horizontal speed of invading cold air (v_o), and phase speed does not influence it but enables the mass of cold air to fall in a strong unbalanced state due to much warmer air on the opposite side of the ridge.

The vertical downward buoyancy acceleration due to temperature differences is in a simplified form

$$\mathrm{d}w/\mathrm{d}t = g\,(T - T')/T' \tag{3}$$

and starts to act on the cold air bulge. In our opinion, due to surface friction it not only slips but also rolls down the slope. By such rolling (by very small surface friction and in developed general flow, also small frontal drag) its speed increases rapidly.

Integrating Eq. (3) by neglection of Coriolis and frictional forces but considering initial temperature differences, adiabatic heating, lapse rate in the warm air (γ') and inclination of the slope (3), so that $w = v \sin \beta$, the approximate average speed of the cold air roll at the foothill of the height h, can be presented by

$$v = v_o + (2\,a\,h - b\,h^2)^{1/2} \;/\; \sin \beta \tag{4}$$

where

$$a = g\,(T_o - T_o') \;/\overline{T}' \quad \text{and} \quad b = g\,(\gamma_d - \gamma')/\;\overline{T}'$$

Calculated speeds for an example show, that the speeds of cold air rols only a little exceed the measured average speed in bora some hundred meters above the surface, due to complete neglection of friction and drag.

The rolling unit of cold air is supposed to take a cylindric form, and depicting a cycloid, creates in its upper border double the speed of its axis and a small one at the surface. There is no pure rolling in bora, due to intertial stress, turbulence and slip. In this way, however, the downsloped speeds in the upper part of cycloids can many times exceed the average speeds of the bora flow near the surface.

The influence of the stress on the surrounding warm air is supposed to create, between two cold cylinders, a cylinder of warm air with the opposite direction of rotation – Fig. 6, D. The whole bora motion is thus a combination of such cylinders in general flow. The first proposition is that the cylinders are approximately circular, but their form may depend on the ratio between amplitude and wave lenght of the original gravity waves.

3.3. The pattern above the sea

This pattern of rolls reaches its maximum velocity at the bottom of the slope and moves away from it. The turbulence is strongly developed of course, but when it is filtered out, a simplified pattern has the form presented in the right side of Fig. 6.

When the life times of large turbulent events are longer than typical times for their advection, the Taylor hypothesis of frozen turbulence is valid (Jensen and Bush, 1982).

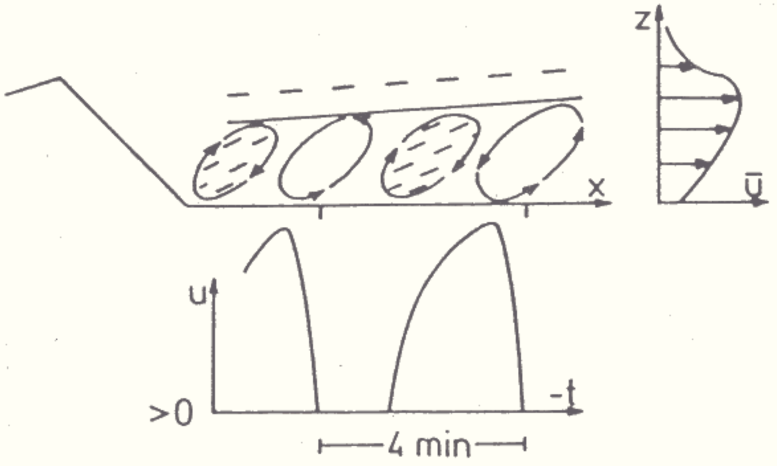

Figure 7. Pattern of rolls, and main bora gusts above the sea.

As in our case these conditions are fulfilled, the passing of the presented pattern should correspond to the registration speed pattern in fixed-point measurements shown in Fig. 4. Obviously they do correspond, but better agreement is obtained, if to this constructed pattern the general vertical wind increase (as observed by Poje, 1982, Jurčec, 1984) is added. A simplified bora pattern constructed in this way is presented in Fig. 7.

The agreement is the best for the case, when the tangential speed in the cold cylinder at the surface is approximately equal to the general speed of the advection of the whole pattern, giving there low speeds or calms. The warm vortex brings down to the surface a high speed or moment, and together with its rotation gives maximal gusts at the surface. In this way the wind speeds in the gusts can exceed three times the average speed of bora near the surface, which has not been explained until now.

It may be shown that the large horizontal moment created in cycloidal motion can be brought down to the surface in the time of a minute by the typical dimensions and rotation of main vortices.

The interesting finding emerging from this consideration is, that the maximum wind speed at the surface in the common cold bora, should be found in the warm vortices of its pattern. Appropriate simultaneous measurements of speed and temperature, that will follow, will be an important indicator of the reality of the presented model.

We already have some confirmation in this way but without measurements, and in the fact: the strongest gusts in the common moderate bora, when the sea spray plume is created, show marked lifting of the spray on its frontal part in agreement with the motion in such a vortex – Fig. 5.

In the pattern of Fig. 7 the increased height of bora flow due to increased instability and upper entrainment is considered too. The static instability is due to advection of colder air above the warmer sea surface. Above the maximum speed of active bora layer, the speed decreases rapidly, as e. g. according to Smith (1984) "just a few hundred meters above violent bora acceleration and deceleration (of aircraft), the air is undisturbed". Due to entrainment and instability in the increased bora thickness, there is a decreasing of kinetic energy density and dissipation as well. Therefore the strength of bora diminishes toward the open sea (Paradiž, 1957), except in the rare cases of strong upper winds in the same direction.

3.4. Some additional remarks and conclusions

That bora is rather specific phenomenon combined from many processes, follows from the comparisons of criteria for scaling. According to the criteria of Emanuel (1983), bora should belong to small scale, because the ageostrophic advection is significant and earth rotation is negligible. According to Wippermann (1981), however, bora belongs to mesoscale, because the essential frequencies are smaller than N (Brunt-Väisälä's). The instability type is somewhere between convective and Kelvin-Helmholtz's with R_i less than zero and horizontal scale about the height of tropopause, but it has with the expression $(\partial\bar{u}/\partial z)^{-1}$ undefined time scale. Bora time scale is obviously defined by N, yet not in bora itself, but in the atmosphere in domain I from where the cold air is invading or being overthrown over the ridge.

It is clear, that this model in a simplified form cannot explain all bora occurrences. However, it agrees with the majority of observations and recognitions, and explains the most important bora property – its violent, but rather periodic gustiness.

List of Symbols

a, b	Parameters defined at Eq. 4
F	Froude number
g	Acceleration of gravity
h'	Height of cold air
h	Height of ridge
N	Brunt-Väisälä frequency
T	Air temperature
T'	Temperature of warmer air
$\bar{T}$	Average temperature
x,y,z	Cartesian coordinates
u,v,w	Wind-speed components
v_0	Initial velocity
γ'	Lapse rate in warmer air
γ_d	Dry adiabatic lapse rate
Θ	Potential temperature

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