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Additional bora characteristics according to the frontal model

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Similarly to the frontal surface, the upper boundary of the bora must be dynamically balanced in a stationary state. Based on this idea, a special bora model, the frontal bora model, was developed in detail and presented elsewhere (Petkovšek, 1990). The model has given some very interesting results; here additional results of numerical experiments are presented. They show how absolute temperature, height of the ridge, inclination and form of the lee side slope influence the bora thickness and speed.

Dodatne značilnosti burje po frontnem modelu

Zgornja meja burje je podobno, kot frontalna površina, meja med dvema različnima zračnim masama in mora biti v stacionarnem stanju dinamično uravnotežena. Na osnovi te ideje je bil zgrajen poseben model burje, t. i. »frontni« model, ki je podrobneje opisan drugje (Petkovšek, 1990) in je dal nekaj novih rezultatov oz. spoznanj. Prikazani so rezultati nadalnjih numeričnih eksperimentov. Ti poskusi kažejo kako vplivajo absolutne temperature, višina grebena, nagib in oblika zavetrnega pobočja na debelino in hitrost burjinega toka.

1. Introduction

Due to strong wind and gusts, measurements in the bora are difficult and uncertain; in the vertical direction, however, the measurements are rather exceptional (Rakovec and Petkovšek, 1983; Smith, 1987; Kennedy, 1892; Poje, 1962). Therefore many important characteristics of the bora flow are know from the models (Smith, 1985; Urbančič, 1984; Petkovšek, 1990). The results somewhat differ, but cannot be directly and exactly verified due to problems of measurements in the bora.

As can be seen in the photos of a typical bora cloud, the upper boundary of the bora is only approximately parallel to the lee side of the slope of the orographic obstacle under it (Fig. 1) because the slope of the upper bora boundary must conform to all dynamical and thermodynamic conditions. Among them some are extremely important; others, however, have quite a small influence and can be neglected. A good and appropriate model must therefore be simple, but still give results which agree with the observations in nature.

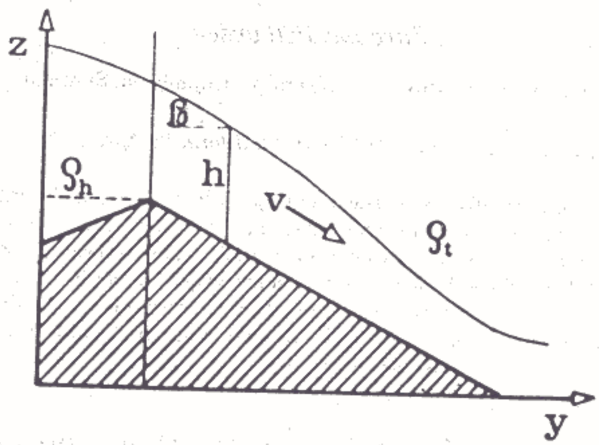

Figure 1. Schematic presentation of the cross-section of an obstacle and the bora flow over it

2. Main characteristics of the model

Our two-dimensional frontal model (Petkovšek, 1990) is based on Margules' equation for the inclination of the frontal surface between two different air masses. Since the bora is mainly an ageostrophic wind and blows within relatively short distances, the terms of the Coriolis force can be neglected, as well as the terms of the centrifugal force. The field of air pressure and the flow adjust themselves over the pure buoyancy due to temperature differences between both air masses and the law of mass conservation. Because the bora is a very gusty wind, the friction is parametrised by the square law of the surface drag.

The introduction of the simplifications presented above in Margules' equation for frontal inclination have produced a set of four partial differential equations: for the ratio of temperatures of both air masses (R), the thickness of the flow (h), the inclination of the upper boundary (β) and the speed (v) of the bora flow.

Using standard notation, the mentioned equations can be written in the form:

$$\partial R/\partial y = -(\gamma_a - \gamma_t)\,(\mathrm{tg}\,\beta + c)/2T_t$$

$$\partial h/\partial y = \mathrm{tg}\,\beta - c$$

$$\partial \beta/\partial y = 1/h - c_r - g(1-R)\,/\,v^2 - (k_k + c/h)\,/\,\mathrm{tg}\,\beta$$

$$\partial v/\partial y = -g(1-R)\,\mathrm{tg}\,\beta/v - k_k v$$

where c, K, T, γ are constants or parameters.

The system of these equations has been solved with the space integration from the points above the ridge of the obstacle downward the flow using the Runge-Kutta method and it gives reasonable, interesting and useful results.

3. The influence of height and inclination of the obstacle

As an addition to the results that were shown at the first presentation of the frontal bora model (Petkovšek, 1990), here we intend to show how the bora flow and its distribution is influenced by the height of the obstacle and its inclination on the lee side. The comparison is given for the winter season when the bora is usually the strongest.

On the ridge of Velebit, over which the bora is formed and spreads about 100 km along the NE coast of the Adriatic Sea, some passes can be found. Under one of them the town Senj is situated, known for a high frequency of bora and having most measurements in the surface bora.

In Senj the bora is probably most frequent, but not the strongest (Bajić, 1989). One would expect it to be strongest, due to better adiabatic heating of the air at the downflow over the lee side slope: however, the influence of the height of the ridge and, consequently, the greater inclination and deformation of the upper boundary of colder air is obviously stronger and more important.

The results of such experiments are presented in Fig. 2, where number 1 denotes typical winter conditions for the ridge of Velebit (h_p1). The pass Vratnik above the town Senj, however, is half of the height of the main ridge (h_p2 in Fig. 2.). When air of the same initial thickness (H_o = 2000 m) is flowing over it the distribution of the flow thickness and speeds of the flow are obtained as presented by curves 2. Obviously, the contraction of the flow is due to a smaller slope inclination, smaller than in case 1, and therefore also the speeds of the bora flow are lower.

However, when the complete region on the windward side of Velebit is filled up with cold air up to the same height a.s.l, the influences are different: an equally thick initial flow of colder air above the Velebit ridge has a thickness of 2000 m, but above the pass Vratnik about 2700 m. Therefore the flow above the upper part of the slope is somehow more contracted and the bora speed here is a little greater (curves 3 in Fig. 2.), but at the lower part of the slope the flow is

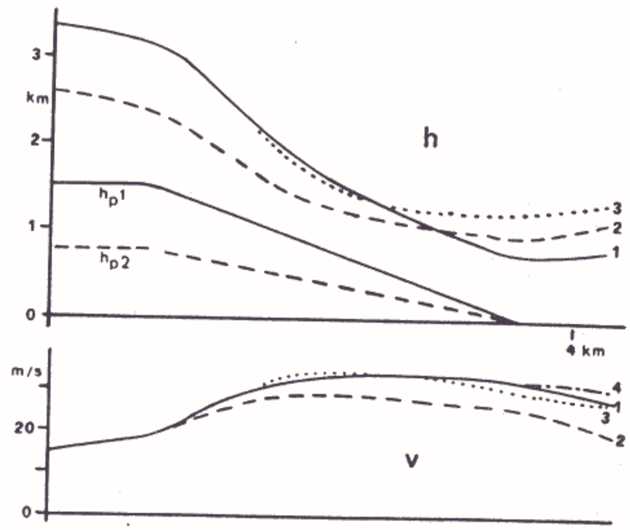

Figure 2. Distributions of the thickness (h) and velocity (v) of the general bora flow for different heights of an obstacle and for different thicknesses of the flow

thicker, and therefore the speeds under the pass and in Senj are smaller than in typical conditions 1, but greater than in conditions 2.

In general conditions the speed of the bora under the pass at Senj is obviously smaller than under the higher ridge of Velebit. In this study, however, the side contraction of the flow through the pass is not taken into account, because it cannot be included in this two-dimensional model.

An additional numerical experiment was made with the smaller friction above the sea (downward from the bottom of the slope) for an order of magnitude. The thickness of the flow here is negligibly different, but the speed of the bora diminishes much more slowly (curve 4). This represents an expected or reasonable behaviour of the model and confirms its value.

4. The influence of the seasons

Further experiments with this model take into account the influence of the seasons or of the absolute air temperatures (not only differences) on the bora speed and thickness (Fig. 3). For summer the values of 26° C, and for winter –4° C were used. The calculations were made for sufficiently great temperature differences between air masses, because it is known that at too small differences (e.g. curves 1) the bora cannot develop.

The season or absolute temperature value does not considerably influence the bora: small differences in speed only can be found with the strong bora (curve 2 winter). The bora is obviously a little stronger in winter (when the

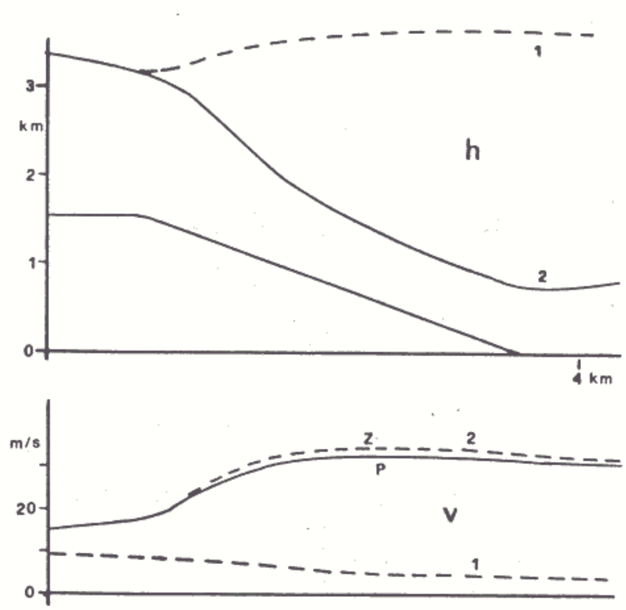

Figure 3 Distributions of the thickness and velocity of the bora for winter (Z) and summer (P) at different temperature differences between both air masses 1: $\Delta T = 2$ K, 2: $\Delta T = 14$ K.

temperature differences between air masses are greater), and also due to lower absolute temperatures.

The climatic studies of the bora (Makjanić, 1970; Lukšić, 1975; Petkovšek and Paradiž, 1976; Yoshio, 1976) show that the bora is really more frequent and stronger in winter than in the other seasons. This is mainly due to the more frequent development of secondary cyclones in the northern Mediterranean. It increases the horizontal pressure gradient over the bora region and diminishes the stability of the warm air mass. For the bora speed this is (as shown by the previous experiments with this model), in the second place in rank of importance. In the first place is the temperature difference between both air masses.

5. The influence of the form of the lee-side slope

Further numerical experiments with this model show the consequences of the lee side slope configuration on the characteristics of the general bora flow. For the form of the obstacle on the lee side a function $\cos^{18}\beta$ (a in Fig. 4) and its mirror form b were taken. The space integration of the system of equations along the slope given by such a function requires (to assure numerical stability) integration in shorter steps. Therefore horizontal distances in the figures are smaller here but this does not influence the comparison between both examples. From the curves in Fig. 4a it can by seen that at the slope, which in the upper

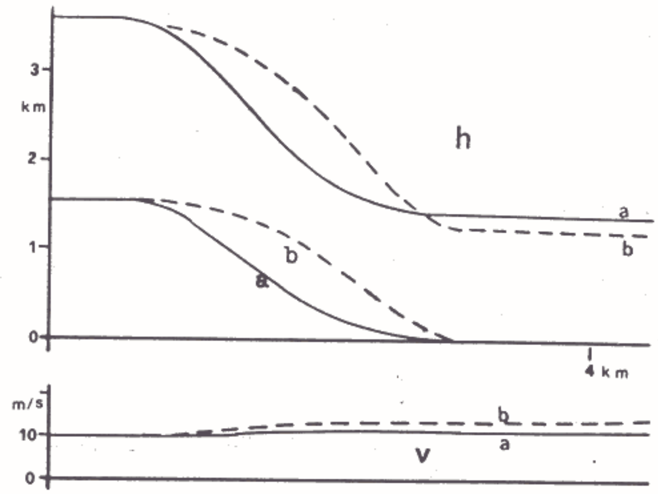

Figure 4. Distributions of the thickness and velocity of the bora for two different forms of the lee side slope of the obstacle.

part decreases quickly and in the lower part slowly changes to a plain (sea surface), the flow first contracts more, but its thickness at the bottom of the slope remains greater. Therefore the final speeds of the bora at the bottom of the obstacle are smaller than at the mirror form of the lee-side slope. Above the slope, which in the upper part slowly changes in steepness which is the greatest at the lower part of the slope (form 4b), the flow at the bottom is more contracted and the bora speed at the bottom and over the sea is somewhat greater. This could be an explanation for different bora speeds along the differently formed ridge of Velebit. Doubtlessly, bora speed is also influenced by the canalisation of the airflow in the ravines and canyons. However this influence can not be included and investigated in this two-dimensional model.

6. Conclusion

These additional numerical experiments with the frontal bora model, which treats the upper boundary of the bora as a dynamically balanced frontal surface, show that a higher ridge and greater inclination of the slope cause stronger contraction of the flow and its higher speed (Fig. 2); that the absolute temperature (season) has only a small influence on the bora speed (Fig. 3); and that the form of the lee side slope (Fig. 4) influences the bora moderately. The additional experiments confirm that the model gives reasonable and interesting results, which are in agreement with the majority of other bora studies and with the terrain observations.

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