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TEMPERATURE DISTRIBUTIONS IN THE BORA UNDER SIMPLE CONDITIONS

Temperaturne razmere ob burji v preprostih pogojih

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Abstract: Assuming simplified initial temperature conditions in the cold and warm air around a mountain obstacle, and using rather elementary relations for temperature changes, the temperature distributions in a cold air flow down the slope were obtained, as well as some interesting results typical of the bora. Two types of flow were treated: flow with air particles moving parallel to the flow boundaries, and a mixed one: in this way the relations between initial conditions and final temperature distriutions in a flow, as well as surface temperatue changes with time at the beginning of the bora, were obtained.

Key words: Bora, Temperature Distributions

Povzetek: Za preproste zatečene temperaturne pogoje v hladnem in toplem zraku okrog gorske pregrade in z uporabo preprostih enačb za temperaturne spremembe, so dobljene temperaturne razporeditive v toku hladnega zraka čez gorsko pregrado, kot tudi zanimivi rezultati, ki so tipični za burjo. Obravnavani sta dve vrsti toka: paralelen tok, kjer so trajektorije zračnih delcev vzporedne z mejami toka in premešani tok: s čemer so dobljenje relacije med začetnimi pogoji in končnimi temperaturnimi razporeditvami v toku, kot tudi možne časovne temperaturne spremebe pri tleh ob začetku burje.

Ključne besede: burja, temperaturne razporeditve

1. INTRODUCTION

Recent extensive, especially vertical or aerial observations of the bora (e.g. Poje 1962, Smith 1982, Jurčec 1984), as well as some models of the bora (Urbančić 1984, Ivančan-Picek 1984, Smith 1985), or models of airflow over ridges (e. g. Bacmeister and Pierrehumbert, 1988), show that the general flow of denser air pouring over a ridge has some characteristics of hydraulic flow. The general part of this flow is approximately adiabatic, and the diabatic influences can usually be neglected. Trajectories of air particles can be more or less parallel to the flow boundaries or isopletes of potential temperature, but they can also be rather unknown in a mixed flow.

A series of unknown quantities such as friction, exchange coefficients, wave and temperature field parameters etc. prevents the creation of reliable bora models and their verification. We therefore believe that many unknown conditions in the bora should first be partially treated and recognized, regarding some fundamental connections among the quantities and their fields. The knowledge obtained will allow more realistic suppositions for complex models and will help in their verification. The rare measurements can be found only in higher layers above the bora and far from the mountain ridge: just in the downslope part of the bora, however, the space measurements do not exist at all.

2. STARTING SUPPOSITIONS

In agreement with recent measurements and physical models of airflow and the distribution of some quantities in the bora and accepted that the two-dimensional flow of colder air over a mountain ridge to the warmer (sea-) side in cross section is like that presented in Fig. 1.

First the main temperature distributions and their connections will be formulated in and around the bora flow. For this purpose let us establish the characteristic heights or levels, and make suppositions of some lapse rates that are in agreement with the theory and observations in cold and warm air, separately.

In agreement with Fig. 1 the following relations should be valid for the chosen levels:

$$\begin{array}{ccccccc} z_g & > & z_p & > & z_b & > & z_o = 0 \\ 2.5 & & 1.5 & & 0.5 & & 0.0 \text{ km.} \end{array} \quad (1)$$

where in the second line presumed typical values are given. At these levels corresponding temperatures (T) are defined and the additional index on the temperature or its lapse rate (γ), means h for cold and t for warm air.

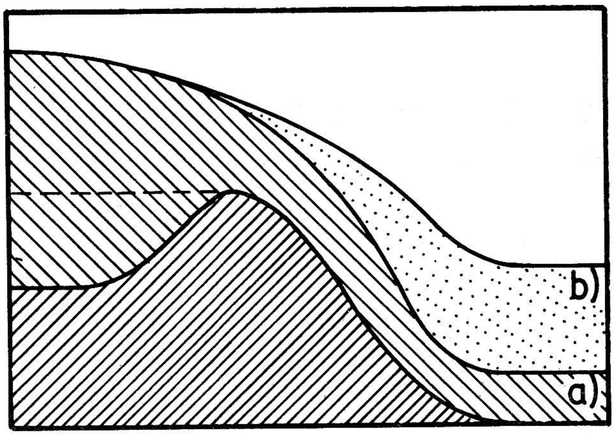

Fig. 1. Schematic presentation of the cross-section of an obstacle and the flow of cold air under warm air on the lee side (for the symbols see text)

Sl. 1. Shematični prikaz preseka pregrade in toka hladnega zraka na njeni zavetrini strani (za pomen simbolove glej tekst)

Further, at approximately the same levels the following relations should be valid:

$$T_{gt} > T_{gh}, \; T_{pt} > T_{pm} > T_{ph}, \; T_{bt} > T_{bh} \qquad (2)$$

To simplify the problem it is supposed that the temperature in the warm air at the level of the mountain ridge, as well as its overall lapse rate, are known and constant: in the cold air, however, this should be so only above the ridge. Therefore

$$T_{pt} = \text{const} \;\; -\partial T_t/\partial z = \gamma_t = \text{const} \;\; T_{pt} - T_{ph} = D_p \qquad (3)$$

In accordance with known relations, the adiabatic flow of cold air down the slope and Fig. 1, the following relations are valid:

$$T_{gh} = T_{ph} - \gamma_{gh}(z_g - z_p) \qquad \text{a) (4)}$$
$$T_{gt} = T_{pt} - \gamma_t (z_g - z_p) \qquad \text{b)}$$
$$T_{ph} = T_{pt} - D_p \qquad \text{c)}$$
$$T_{bt} = T_{pt} + \gamma_t (z_p - z_b) \qquad \text{d)}$$
$$T_{bh} = T_{gh} + \gamma_a (z_g - z_b) \qquad \text{e)}$$
$$T_o = T_{ph} + \gamma_a z_p = T_{bh} + \gamma_b z_b \qquad \text{f)}$$

where the last two are valid for the parallel flow only.

These relations enables us to recognise some important relations about the temperature and its fields, and even some assessments of flow speed. To present separate findings through some examples, the following lapse rates were presumed

	γ_{gh}	γ_t	
less stable	9	8	K/km
typical	8	7	K/km
more stable	6	3	K/km

and of course $\gamma_a = 10$ K/km.

3. PARALLEL FLOW

3.1 Flow conditions

The relation between the lapse rate in a bora flow above the ridge γ_{gh} and that in the bora at the bottom of the obstacle γ_b is obtained from the last relations of Eq. (4f). If relations (4a) and (4e) are introduced, writing shortly for the thickness of the flow above the ridge $z_g - z_p = H$ (which is typically 1 km), the thickness or height of the bora layer at the bottom of the obstacle is obtained from

$$z_b = H(\gamma_a - \gamma_{gh})/(\gamma_a - \gamma_b) \qquad (5)$$

This thickness is obviously proportional to the stability of the cold air above the ridge, inversely proportional to the stability of the flow at the bottom of the obstacle, and is rather various, in agreement with the assessment of Smith's measurements (1987). Typical γ_b can be obtained using Eq. (5), because our idea about the thickness is better than that about γ_b (Jurčec 1981, Poje 1962).

Let us use a simple form of the continuity of the mass flow law

$$\rho_g v_g H = \rho_b v_b z_b \qquad (6)$$

where ρ and v are average densities and speed of the flow above the ridge (g) and at the bottom (b). It is known that the flow speed of an incompressible fluid depends on the confluence of the borders. The relative speed of the bora at the bottom of the ridge can therefore be approximately determined if z_b is known or assessed. The speed of the flow at the bottom of the ridge is usually enlarged due to this reason only

$$v_b = v_g (H/z_b)(\rho_g/\rho_b) \qquad (7)$$

where the last factor - the density ratio - depends on the height of the ridge and is nearly constant in the presented examples i.e. $(\rho_g/\rho_b) = B$ is about 0.8.

According to Eq. (5) the following equation for the flow speed at the bottom is also valid

$$v_b = v_g B(\gamma_a - \gamma_b)/(\gamma_a - \gamma_{gh}) \qquad (8)$$

It follows that for $\gamma_b = \gamma_a$ the speed has to be $v_b = 0$: for every $v_b > 0$, however, there must be then $\gamma_b < \gamma_{gh}$. The atmosphere of such a flow approximately along the surfaces of equal potential temperature is not only warmed but stably stratified as well. Under considerable contraction of the flow at the bottom of the ridge, the speed of bora is also approximately greater due to this reason.

Additionally it must be true that the border condition on the level z_b is $T_{ph} < T_{bt}$, otherwise the advected cold air could not reach the bottom of the obstacle. Using this condition and the appropriate relations of Eq. (4), the necessary initial temperature difference between a cold and warm air mass on the level of the mountain ridge $T_{pt} - T_{ph} = D_p$, must be large enough: namely

$$D_p \geq \gamma_a (z_g - z_b) - \gamma_{gh} H - \gamma_t (z_p - z_b) \quad (9)$$

For the assumed typical values. $D_p = 5.0$ K is obtained. So much colder must be the cold air to reach the bottom of the obstacle at all. In the assumed more labile atmosphere the necessary temperature difference can be smaller $D_p = 3.0$ K: in the stable 11.0 K, however. The observed differences can be even greater (e. g. Vučetić, 1985). In the case of the given typical values, the speed at the bottom of the ridge is increased, due to confluence of trajectories only - $v_b = 1.6\ v_g$. A larger number of examples show that the stabilities of the cold and warm air influence rather equaly on D_p, but the influence of the foot flow thickness is realtively small, however.

A rearranged Eq. (9) enables to calculate the relative height of the upper level of the bora layer without known γ_b (needed in Eq. 5), thus

$$z_b/H \geq [(z_g \gamma_t - z_p \gamma_t - D_p)/H - \gamma_{gh}] / (\gamma_a - \gamma_t) \quad (10)$$

Using this relation, for the typical values again a typical compression of flow to half is obtained $z_b/H = 0.5$: under assumed more stable conditions, however, for a diminished relative flow thicknes at the bottom $z_b/H < 1$, the initial temperature difference must be greater: $D_p > 7.0$ K.

The cold air flow over the ridge and downward the slope is usually lowered and accelerated due to dynamic reasons that will be treated elsewhere (Fig. 2). From here obtained temperature conditions only, it follows, that at the temperature difference between the air masses $D_p = 5$ K in our typical conditions, the flow downward the slope is accelerated and confluenced, reaching its highest speed at the bottom of the obstacle (Fig. 2 line a). In the stable stratification of air masses, however, the flow can be difluent ($z_b/H > 1$), and the greatest speed of the bora is somewhere above the ridge (line b). For a flow speed over the ridge e.g. $v_g = 15\ m\ s^{-1}$, Eq. (7) gives the average bora speed at the bottom $v_b = 24\ m\ s^{-1}$, in the case b), however, it is only $9\ m\ s^{-1}$. The stability of the air masses thus has an important influence on the bora speed at the bottom of the obstacle.

3.2 Temperature at the border of air masses

Let us now consider the temperature differences in an inversion along the border between the air masses. The condition of Eq. (9) shows that on equality the difference at the level z_b is zero, and there is no temperature inversion separating both air masses, which can therefore easily mix. Let us establish also the temperature difference at the border of masses also at the height of the ridge z_p, remembering that D_p does not represent the difference at the border but, regarding to cold air, at the ridge (Eq. 4c). The temperature difference at the border of air masses at the height z_p is

$$D_m = T_{pt} - T_{pm} \quad (11)$$

or in accord with the relations of Eq. (4)

$$D_m = D_p - H (\gamma_a - \gamma_{gh}) \quad (12)$$

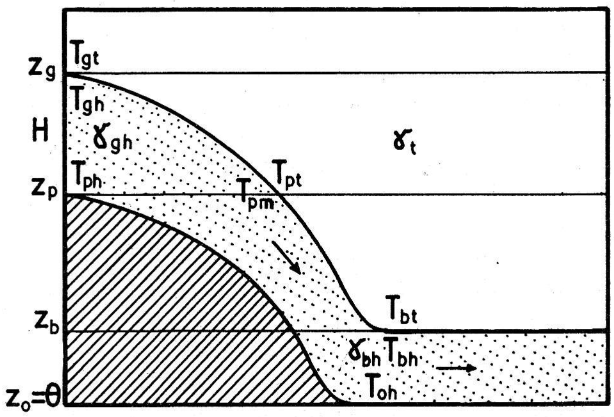

Fig. 2. Cold air or bora flow that is, in accord with stability of air masses, downward the slope contracting a) or thickening b) (for the symbols see text)

Sl. 2. Tok hladnega zraka, ki se v skladu s stabilnostjo zračnih mas ob pobočju navzdol stiska a) širi b)

which gives for typical values $D_m = 3.0$ K. At the border above the ridge, however, the temperature difference is

$$D_g = T_{gt} - T_{gh} = D_p + H (\gamma_{gh} - \gamma_t) \quad (13)$$

and gives for typical values $D_g = 6.0$ K. The temperature difference at the border of both air masses therefore decreases downward the parallel flow. If the colder air is not cold enought, in accord with the Eq. (9), such a flow at the bottom of the obstacle does not exist.

3.3 Temperature changes at the surface

It is interesting to know how strong the cooling or temperature decrease is on the surface at the foot of the obstacle at the beginning of bora flow. In general, bora is known as a cool wind, and realy e.g. in Senj the temperatures on the days with bora are on an average 3 to 6 K lower than on days without bora (Lukšić 1975). However, it is not always so (Jurčec, 1981: Brebrič, 1983; Pristov, Petkovšek, Zaveršek, 1988).

From Fig. 3 and the data on level z_p it is obvious that the starting temperature T_{oo} (before bora begins) and "final" T_{ok} (in bora) at the surface are given by:

$$T_{oo} = T_{pt} + \gamma_t z_p\ ,\ T_{ok} = T_{ph} + \gamma_a z_p \quad (14)$$

If temperature change with time is defined by $D_o = T_{ok} - T_{oo}$, cooling appear for Do < 0. From the given relations and Fig. 3 one can find

$$D_o = z_p (\gamma_a - \gamma_t) - D_p \quad (15)$$

which means, that at a lower obstacle the coolings are greater and/or under cols of a ridge more frequent. From Eq. (15) one can obtain the first condition for cooling at the footline at a given γ_t regarding the temperature difference at the ridge level

$$D_p > z_p (\gamma_a - \gamma_t) \tag{16}$$

or with the sign < for warming. Apart from the height of the ridge, the sign here depends on the lapse rate in the warm air. In typical conditions, for cooling the initial temperature difference on ridge level must be $D_p \geq 4{,}5$ K: for presumed more labile warm air $D_p \geq 3.0$ K. however, and for stable air $D_p \geq 10{,}5$ K. In the presumed typical conditions for $D_p = 5.0$ K (at Eq. (9)), cooling at the surface will be found, but at $D_p < 4{,}5$ (what is possible by Eq. (10) at greater z_b only), the air temperature at the surface at the beginning of bora will rise.

The rearranged form of Eq. (16) gives the conditions for cooling - regarding the lapse rate of the warm air

$$\gamma_t > \gamma_a - D_p/z_p \tag{17}$$

and with the opposite sign of inequality for warming. For typical conditions the border is by $\gamma_t = 6.7$ K/km. The cases are clearly presented in Fig. 3. From this it is obvious, that also when the last condition of Eq. (2) is met, that enables the lowering of the air to the foot, bora can cause there warming or temperature increase at the surface.

As the air can reach the foot of the obstacle at the condition of Eq. (9) only, warming or cooling depends on the thickness of the bora on level z_b as well. Therefore the condition for cooling demands usually a greater temperature difference on the level of the ridge, namely

$$D_p > H (\gamma_a - \gamma_{gh})\, z_p/z_b \tag{18}$$

For typical conditions now $D_p = 6.0$ K is obtained. Aparat from the contraction of flow, for the temperature difference at the surface, the lapse rate and the thickness of the cold air above the ridge are decisive as well. Obviously the conditions of Eqs. (16) to (18) must be fulfilled so that bora at the foot will be accompanied with a decrease of temperature - broken line in Fig. 3.

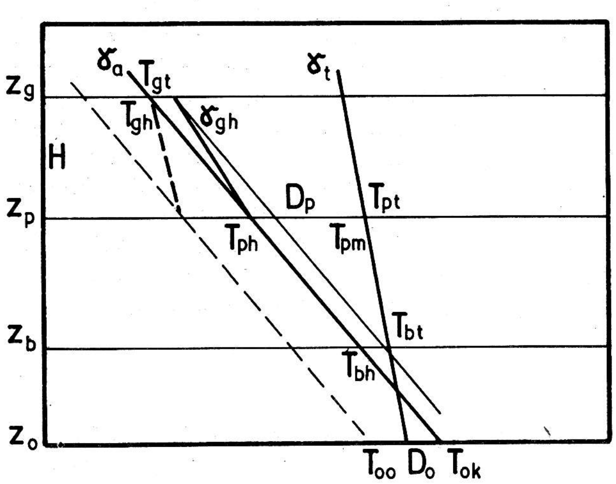

Fig. 3. Temperature lapse rates in a warm air, and cold air flow over an obstacle in a parallel flow (for the symbols see text)

Sl. 3. Vertikalne temperaturne razporeditve v toplem zraku inv toku hladnega zraka čez pregrado (za pomen simbolov glej tekst)

4. MIXED BORA FLOW

Due to different waves, turbulence and some special phenomena inside the bora flow (Poje 1962, Petkovšek 1987) there are small chances, that the trajectories of air particles in a flow downward the slope would be parallel to the boundaries of the flow. More probably the flow is soon mixed; then however, in the foot flow $\gamma_b = \gamma_a$ is possible. Due to adiabatic heating there is a warming of the whole flow and an increase of its mean temperature, but in the upper part of the flow the temperatures are lower, and in the lower part higher than before in the parallel flow, because the heat flux of an initially stable layer is oriented downward by overmixing.

Regarding Fig. 4 also for a mixed flow the Eqs. (4a-d) are valid, otherwise for the mean temperature of the flow the following partly simplified equation can be written

$$T_{bh} = T_{ph} - \gamma_{gh} H/2 + \gamma_a [(z_g + z_p - z_b)/2] \tag{19}$$

Because the lapse rate in the flow at the footline of the obstacle is adiabatic now, we have

$$T_{oh} = \overline{T}_{bh} + \gamma_a z_b/2 \text{ and } \overline{T}_{bh} = \overline{T}_{bh} - \gamma_a z_b/2 \tag{20}$$

In comparison with the parallel flow, now in the mixed flow at the border with the warm air, the cold air is cooler but at the surface warmer. The cold air or the bora flow in these conditions more easily reaches the foot, but more often demonstrates with warming. New initial conditions, that would enable the mixed flow to reach the foot of the obstacle are now

$$D_p \geq \gamma_a [(z_g + z_p)/2 - z_b] - \gamma_{gh} H/2 - \gamma_t (z_p - z_b) \tag{21}$$

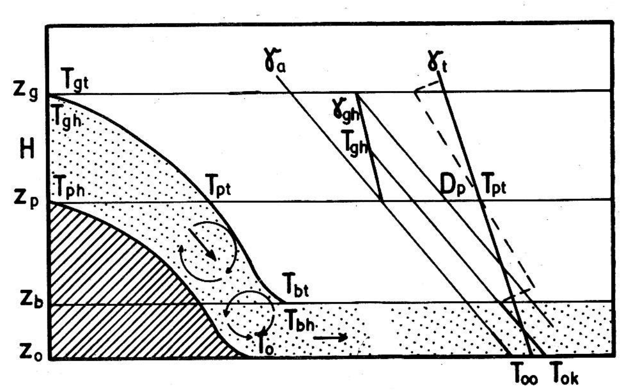

Fig. 4. Schematic presentation of the coss-section of the obstacle and atmosphere above it (left), and corresponding temperature distributions in and around a mixed flow (right) (see text)

Sl. 4. Shematični prikaz preseka tmosfere ob pregradi (levo) in ustreznih temperaturnih razporeditve (desno) pri premašanem toku za precej stabilne razmere (za pomen simbolov glej tekst) which gives for presumed less stable, typical and more stable conditions 2.5, 4.0 and 9.0 K. Comparison of examples will be seen in Table 1. From the Eq. (21) it follows, that regarding D_p in the mixed flow, the stability of warm air is approximately twice as effective as the stability of the cold air.

The temperature inversion separating both air masses vanishes at the sign of equality of Eq. (21) and the masses mix there. This vanishing happens in comparison with the parallel flow now at a smaller D_p. On the level z_p the temperature difference at the border of masses is not simply defined, because it is not known if the bora layer is already completely mixed. The temperature difference between air masses on the level z_g is supposed to be aproximately the same as before in paralell flow, and is given by Eq. (13). It is obvious, that the temperature difference on the border of air masses diminishes downwards in both cases.

The changes of temperature in time at the surface at the beginning of bora are defined with the final temperature, that is according to Fig. 4 in the mixed flow now

$$T_{ok} = T_{ph} - \gamma_{gh}H/2 + \gamma_a (z_g + z_p)/2 \qquad (22)$$

The initial temperature T_{oo} is the same as before, (the first of Eqs. (14)). Instead of Eqs. (16) and (18), now for the mixed flow the condition for the cooling at the surface is

$$D_p > \gamma_a (z_g + z_p)/2 - \gamma_{gh}H/2 - \gamma_t z_p \qquad (23)$$

and in the mixed flow does not depend on z_b. For the presumed less stable, typical and more stable conditions for D_p: 3.5, 5.5 and 12.5 K is obtained now. For cooling at the surface in the mixed flow, greater initial temperature differences of air masses are necessary. Especially in stable conditions the temperature differences are to be great, otherwise the bora at its beginning will appear at the surface with warming.

By the rather shallow flow of cold air over the mountain obstacle, the temperature differences at the surface are obviously more dependent on γ_t than γ_{gh}. Because at the time of a Mediterranean cyclone over the region, the warm air layers due to a general lifting of the air, are less stable, γ_t is large, and bora gives coolings at a smaller initial air mass temperature differences. By prevailing anticyclone, however, warming at the surface should be more frequent. Because in the first case the sky is usually overcast but in the second clear, the appropriate temperature changes can easily be wrongly assigned to the influence of insolation, which is in rather turbulent bora less important, however: although a marked daily course of air temperature in bora has been observed also (Jurčec 1981, Pristov, Petkovšek, Zaveršek 1988).

It can be seen from the Table, that for the parallel flow larger initial temperature differences between air masses (Eq. 9) are necessary to reach the foot, than by the mixed flow (Eq. 21), which is internally by mixing cooled

Table 1. The smallest D_p at the presumed conditions that: a) enables the decrease of the flow to the foot of the obstacle, b) enables coolings at the foot surface at the beginning of bora: for both types of flow downward the slope (in K)

Tabela 1 Najmanjši D_p pri postavljenih pogojih, ki: a) omoguča spust toka v podnožje pregrade in b) omogoča nastop ohladitev v podnožju pri tleh ob pričetku burje, za obe vrsti toka burje ob pobočju navzdol (v K)

	a,		b,	
flow:	parallel	mixed	parallel	mixed
equation:	(9)	(21)	(18)	(23)
less stable	3,0	2,5	3,0	3,5
typical	5,0	4,0	4,5	5,5
more stable	11,0	9,0	10,4	12,5

in the upper part, and warmed in the lower. The opposite can be found by the temperature changes with time at the surface: for the cooling effect in parallel flow smaller initial temperature differences are necessary (Eq. 18) than for the mixed flow (Eq. 23). Probably the bora flow in nature is rather (although may be not completely) mixed, and the mixed flow is nearer to that in nature.

Smith (1985) states in his model, that in some cases the warm air under the height of z_g is mixed well, and this air is after him as after Bacmeister and Pierrehumbert (1988) bordered by the reflection layer for internal waves and turbulence. In the mixed warm air the stratification is then more labile, which forms on both borders of this layer temperature inversions - broken lines in Fig. 4. The lower inversion is at the height of z_b and enables the bora flow to the foot of the obstacle at smaller initial temperature differences, at the surface the coolings are greater, however. This puts in doubt the statement of Brebrić (1983) that by bora the stability of air masses in the windward side is more important than on the lee side.

5. CONCLUSION

The presented thermodynamic and temperature connections and fields in a cold flow and around it, show many peculiarities regarding the flow of the cold air over a mountain ridge or obstacle, which is typical for bora. Rather rare exaustive analyses confirm most of them (Sijerković 1980, Jurčec 1981, Poje 1962, Pristov, Petkovšek, Zaveršek 1988). There are some aerial measurements above bora and far from the ridge as well that agree also. In the bora flow directly along the slope, however, measurements do not exist at all, because bora does not allow them. We believe that the results of bora models must be in agreement with the presented and rather simply obtained results, and that these will be of help while constructing and verifying more complex bora models.

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