CASE STUDIES OF THE BORA WIND. NUMERICAL SIMULATIONS IN THREE DIMENSIONS

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Abstract

Section 3, line 1:
reads: ... simulates the two days well, ...
should read: ... simulates the main characteristics of the two days well, ...

Chapter 2.

Page 6, line 3 and 4 should read:
The liquid water potential temperature $\Theta_l$ is given by equation (12), where
the radiative heating/cooling rate $Q_R = 0$, and instead of using the energy
balance at the surface, $T_{\text{land}}$ and $T_{\text{sea}}$ are assigned.

Chapter 4.

Page 9, last section, line 5:
reads: ... the wind accelerates where the mountains begin to rise, ....
should read: ... the wind accelerates on the upstream side where the
mountains begin to rise, ...

Page 10, Figure 3:
reads ... 22 March.
should read: ... 22 March 1982.

Page 11, line 5:
reads: ... to southwesterly inside the bora layer.
should read: ... to northeasterly inside the bora layer.

Chapter 5.

Page 16, last section, line 1; page 19, line 1; page 22, line 1;
page 25, line 1:
reads: ... wind speed variance in the z-direction...
should read: ... vertical wind speed variance ...

Figures: 14, page 17; 18, page 19; 23, page 22; 28, page 25
reads: ... wind speed variance in the z-direction...
should read: ... vertical wind speed variance ...

and $W$ should be replaced with $w^2$.

Page 24, line 3:
reads: ... the northern part of the area.
should read: ... the northern part of the area ($y \approx 80$ km).

Page 27, section 3, line 1:
reads: ... simulates the two days well, ...
should read: ... simulates the main characteristics of the two days well, ...

Chapter 6.

Page 28, section 4, line 1:
reads: ... simulates the two days well, ...
should read: ... simulates the main characteristics of the two days well, ...
Abstract

Two days with bora has been numerically analysed, using a three dimensional hydrostatic mesoscale model developed at the Department of Meteorology, Uppsala University. The two simulated days, 22 March and 15 April 1982, have been compared to aircraft measurements done during the ALPEX-SOP in 1982. The model area was the northeastern shore of the Adriatic Sea.

The bora on 15 April was easier to simulate than the one on 22 March, mostly due to the fact that this bora was shallower than the one on 22 March, and since the used model is developed for mesoscale studies, it works better with smaller scales (on the mesoscale). The simulations show that the bora character is a function of both time and space, for example changes in turbulence intensity. Three dimensional effects play an important role, for example channelling effects, which was also confirmed by the simulations.

Compared to measurements, the model simulates the two days well, especially 15 April. All the significant features of the bora wind were well simulated, the wind speed maximum at the ridge crest, the descent of isotherms and isolines of specific humidity downstream the crest, channelling effects etc. The turbulence was not always present just above the ridge crest, but at some times and some places it was well simulated. The most difficult variables to simulate was the specific humidity and the potential temperature.
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1. Introduction

Many places around the world are affected by special local weather phenomena, one of those places is the eastern shore of the Adriatic Sea, between Trieste in north and Dubrovnik in south, where the so called bora\textsuperscript{1} blows. The mountains which causes the bora is the Dalmatian mountains with heights between 700 and 1800 meters. The name "bora" is used all around the world as a name for this special type of downslope wind, but the origin area is the one mentioned above. This cold, dry and gusty downslope wind is of great interest for the people living in the area. It can start very suddenly and for traffic, buildings, bridges etc. it can be hazardous and cause great damage; the vegetation is also affected. The bora is known for its violent gusts, and can exceed the average velocity by a factor three or more, typical average wind speed is between 10 and 15 m/s with gusts that exceed 50 m/s. In experience of fishermen, the gusts repeat every three to four minutes, and may be encountered up to 60 km offshore. Typical duration of the bora is one day, but it can continue to blow up to 2 weeks. It is more common with bora in the winter than in the summer and it often has a late nocturnal maximum between 5 and 8 a.m. (Barry 1992). The bora has often been classified as a pure fall wind, which accelerates due to its low temperature and greater density as it moves downslope, but Smith (1987) finds no verification of this idea in his analysis of the results from the ALPEX project in March and April 1982. It is rather a combination between the approach of cold air from northeast and specific synoptic situations.

Other places around the world have similar winds, for example Boulder, Colorado. The mountains which causes this downslope wind is the Rocky mountains. Due to its high population and high frequency of meteorologists, this wind is quite well analysed, see for example Klemp and Lilly (1975). Even if it is similar to bora in many ways, there is one big difference, Boulder has no coastline.

Many attempts to numerically simulate flow over mountains have been made, especially in two dimensions, see for example Klemp and Lilly (1975). Numerical simulations of airflow over mountains in three dimensions have been more common in later years, mostly owing to faster computers, see for example Miranda and James (1992).

The bora has been object for several numerical simulations (Hoinka 1985; Petkovšek 1987), but these simulations are mainly in two dimensions. The intent of this work is to make numerical case studies of two days, 22 March and 15 April 1982, of the bora wind, using a three dimensional mesoscale model developed at the department of Meteorology, Uppsala University. This model have previously been used in both two and three dimensional studies of mesoscale circulations (Andrén 1990; Enger et al. 1993; Grisogono 1995; Tjernström 1987; Tjernström 1988).

\textsuperscript{1}From the Greek βορέας, which means north wind.
2. Theoretical background for the simulations

The behaviour of airflow over an obstacle, in this case a mountain, depends principally on (1) the vertical wind profile, (2) the stability structure, and (3) the shape of the obstacle. The horizontal scale for airflow over mountains are between one and a couple of hundred km, which allows the use of a mesoscale model for simulations.

2.1. Mountain meteorology - an analytical view

Air forced to flow over a mountain creates oscillations which can be either vertically propagating or vertically decaying. These gravity waves, called lee waves are very important for downslope winds. An spatial equation for the fluctuation, $w'$, of the vertical velocity is given by (Holton 1992):

$$\left( \frac{\partial^2 w'}{\partial x^2} + \frac{\partial^2 w'}{\partial z^2} \right) + l^2 w' = 0 \quad (1)$$

where $l$ is the Scorer parameter, defined as

$$l^2 = \frac{N^2}{u^2} - \frac{1}{u} \frac{d^2 u}{dz^2} \quad (2)$$

and $N$ is the Brunt-Väisälä frequency (or the buoyancy frequency), given by

$$N^2 = g \frac{d \ln \theta_0}{dz} \quad (3)$$

where $\theta_0$ is the potential temperature.

If the mean cross-mountain wind speed increases strongly with height, or there is a low-level stable layer so that $N$ decreases strongly with height, there may be a layer near the surface in which vertically propagating waves are permitted, which is topped by a layer in which the disturbance decays in the vertical. In that case vertically propagating waves in the lower layer are reflected when they reach the upper layer. Under some circumstances the waves may be repeatedly reflected from the upper layer and the surface downstream, leading to a series of "trapped" lee waves. Vertical variations in the Scorer parameter can also modify the amplitude of waves that are sufficiently long to propagate vertically through the entire troposphere. Amplitude enhancement leading to wave breaking and turbulent mixing can occur if there is a critical level where the mean flow goes to zero $l \to \infty$. 
Another theory for downslope winds is the so called "hydraulic jump theory". Assume that the troposphere has a stable lower layer of undisturbed depth $h$ topped by a weakly stable upper layer, and that the lower layer behaves as a barotropic fluid with a free surface $h(x, t)$. Assume also that the disturbances have zonal wavelength much greater than the layer depth. The linearized shallow-water equations for steady flow over a small-amplitude topography is then given by (Holton 1992):

$$
\bar{u} \frac{\partial u'}{\partial x} + \frac{g \delta \rho}{\rho_1} \frac{\partial h'}{\partial x} = 0
$$

$$
H \frac{\partial (h' - h_M)}{\partial x} + H \frac{\partial u'}{\partial x} = 0
$$

(4 a, b)

where $\bar{u}$ is the constant basic state zonal velocity, $h_M$ is the height of the topography, $\delta \rho/\rho_1$ is the fractional change in density across the interface between the layers, $h' = h - H$, where $H$ is the mean height of the interface, and $h' - h_M$ is the deviation from $H$ of the thickness of the lower layer. (4a) is the x-momentum equation, and (4b) the continuity equation, which can be solved with linear methods. The solutions to equation (4a) and (4b) then can be expressed as

$$
h' = \frac{-h_M \left( \frac{\bar{u}^2}{c^2} \right)}{\left( 1 - \bar{u}^2/c^2 \right)}
$$

$$
u' = \frac{h_M \left( \frac{\bar{u}}{H} \left( \frac{\bar{u}}{1 - \bar{u}^2/c^2} \right) \right)}{\left( 1 - \bar{u}^2/c^2 \right)}
$$

(5 a, b)

where $c^2 = (gH \delta \rho/\rho_1)$ is the shallow-water wave speed. The Froude number $Fr$ is defined as $Fr^2 = \bar{u}^2/c^2$ and is the ratio between inertial force and buoyancy force. When $Fr < 1$, the flow is called subcritical and the gravity wave speed is greater than the mean flow speed. When $Fr > 1$, the flow is called supercritical and the mean flow speed is greater than the gravity wave speed. For $Fr \approx 1$ the perturbations are no longer small and the linear solution breaks down. The nonlinear equations corresponding to equations (4a) and (4b) in the case $\delta \rho = \rho_1$ can be expressed as

$$
u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} = 0
$$

$$
u \left( \frac{\partial (u - h_M)}{\partial x} \right) = 0
$$

(6 a, b)

The solution to equation (6a) gives that the sum of kinetic and potential energies is constant following the motion. In addition, the mass flux $u(h - h_M)$ must also be conserved. The direction of the exchange between kinetic and potential energy in flow over a ridge is determined by that both (6a) and (6b) are satisfied. Combining these two we get

$$
\left( 1 - Fr^2 \right) \frac{\partial u}{\partial x} = \frac{ug \frac{\partial h}{\partial x}}{c^2}
$$

(7)
where the shallow-water wave speed is now defined using the local thickness of the fluid:

\[ c^2 = g\left(h - h_M\right) \]  

(8)

The flow will accelerate on the upslope side of the ridge if the Froude number is less than unity (subcritical flow), but will decrease if the Froude number is greater than unity (supercritical flow). As a subcritical flow ascends the upslope side of a topographic barrier, Fr will tend to increase both from the increase in u and decrease in c. If Fr = 1 at the crest, the flow will become supercritical and continue to accelerate as it descends the lee side until it adjusts back to the ambient subcritical conditions in a turbulent hydraulic jump. In this case very high velocities can occur along the lee slope since potential energy is converted into kinetic energy while the flow passes the barrier.

The situations described above are most important for flow in two dimensions. At low Froude numbers effects in three dimensions come into play (Miranda and James 1992) with splitting streamlines around the mountain. Unfortunately, there is no general theory for three dimensional mountain gravity waves, which play an important role for the development of bora. Thus, we proceed with numerical modelling.

2.2. Model description

The model used for the bora simulations is a three dimensional, hydrostatic mesoscale model developed at the Department of Meteorology, Uppsala University. Enger et al. (1993) and Grisogono (1995) shows that the model can simulate nonlinear flows in mountain areas, and indicates that it also would simulate bora successfully.

2.2.1. Basic equations for the model

The model uses a terrain following coordinate system, and the new vertical coordinate is defined as

\[ \eta = s - \frac{z - z_g}{s - z_g} \]  

(9)

where s is the top height of the model, z the actual height and \( z_g \) the height of the terrain.

The basic equations transformed to this new coordinate system are as follows:

\[ \frac{dU}{dt} = \left( \frac{s}{s - z_g} \right)^2 \frac{\partial}{\partial \eta} \left( K_{st} \frac{\partial U}{\partial \eta} - fV_g - \Theta_x \left( \frac{\partial \pi}{\partial x} \right)_{\eta = \eta_c} \right) + 
\]

\[ + g \frac{\eta - s}{s} \frac{\partial z_g}{\partial x} + fV \]  

(10)

\[ + g \frac{\eta - s}{s} \frac{\partial z_g}{\partial x} + fV \]
\[
\frac{dV}{dt} = \left( \frac{s}{s-z_G} \right)^2 \frac{\partial}{\partial \eta} \left( K_M \frac{\partial V}{\partial \eta} \right) + fU_s - \Theta_v \left( \frac{\partial \pi}{\partial y} \right)_{\eta=e} + \\
+ g \frac{s-z_G}{s} \frac{\partial z_G}{\partial y} - fU
\]
(11)

\[
\frac{d\Theta_l}{dt} = \left( \frac{s}{s-z_G} \right)^2 \frac{\partial}{\partial \eta} \left( K_{H} \frac{\partial \Theta_l}{\partial \eta} \right) + \sigma_R
\]
(12)

\[
\frac{dq}{dt} = \left( \frac{s}{s-z_G} \right)^2 \frac{\partial}{\partial \eta} \left( K_{H} \frac{\partial q}{\partial \eta} \right)
\]
(13)

\[
\frac{\partial \pi}{\partial \eta} = -g \left( \frac{s-z_G}{s} \right) \frac{1}{\Theta_v}
\]
(14)

where

\[
\frac{d}{dt} = \frac{\partial}{\partial t} + U \frac{\partial}{\partial x} + V \frac{\partial}{\partial y} + W^* \frac{\partial}{\partial \eta}
\]
(15)

\(U, V\) and \(W^*\) are mean wind speed components in \(x, y\) and \(z\)-directions and \(U_s\) and \(V_s\) is the geostrophic wind components. \(K_{H}\) and \(K_M\) are the turbulent exchange coefficients for heat and momentum, \(f\) the Coriolis parameter and \(h\) is defined as:

\[
h = \eta \left( \frac{s-z_G}{s} \right) + z_G
\]
(16)

\(\Theta_v\) is the mean value of the virtual potential temperature and \(\pi\) a scaled pressure (the Exner function) defined as:

\[
\pi = c_p \left( \frac{p}{p_0} \right)^{R \mu / c_p}
\]
(17)

where \(p\) is the pressure, \(p_0\) a reference pressure (1000 hPa), \(c_p\) specific heat at constant pressure and \(R\) the gas constant for dry air (287.06 J/kg·K).

The first term on the right hand side of equations (10) and (11) is the turbulence exchange. The second, third and fourth terms the pressure terms. The second term is the large scale pressure force, expressed with the geostrophic wind, the third term is dependent on the field of the mesoscale pressure perturbation (dependent indirectly on the
terrain and the temperature field via the hydrostatic equation), and the fourth term is dependent directly on the terrain. The fifth term is the Coriolis term.

The liquid water potential temperature $\Theta_l$ is given by equation (12) where $\sigma$ is the radiative heating/cooling rate, in this case assigned by $T_{\text{Land}}$ and $T_{\text{snow}}$. The specific humidity is given by equation (13). A necessary condition for the hydrostatic approximation is that the terrain slope $<< 45^\circ$, and the approximation is given by equation (14).

Since the new coordinate system is introduced, the equation of continuity becomes:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W^*}{\partial \eta} = \frac{1}{s - z_g} \left( U \frac{\partial z_g}{\partial x} + V \frac{\partial z_g}{\partial y} \right)$$

(18)

$U$ and $V$ will have the same magnitudes as in a Cartesian coordinate system, even if the direction is not the same. $W$, on the other hand, does not have this advantage and the Cartesian coordinate can be calculated as:

$$W = (\frac{\partial \eta}{\partial z})^{-1} \left( W^* - U \frac{\partial \eta}{\partial x} - V \frac{\partial \eta}{\partial y} \right)$$

(19)

The turbulent kinetic energy $Q$ is calculated, based on a higher-order closure scheme (Andrén 1990), as:

$$\frac{d Q^2}{d t} = \left( \frac{s}{s - z_g} \right)^2 \frac{\partial}{\partial \eta} \left( E_3 Q_l \frac{\partial Q^2}{\partial \eta} \right) + 2 \frac{s}{s - z_g} \left[ -uw \frac{\partial U}{\partial \eta} - \nu w \frac{\partial V}{\partial \eta} \right] +

+ 2 \beta g w \theta_v - 2 \frac{Q^3}{B_l l}$$

(20)

where

$$(-uw, -\nu v) = \frac{s}{s - z_g} K_M \left( \frac{\partial U}{\partial \eta}, \frac{\partial V}{\partial \eta} \right)$$

(21)

and

$$-w \theta_v = \frac{s}{s - z_g} K_H \frac{\partial \Theta_v}{\partial \eta}$$

(22)

$E_i$ and $B_i$ are closure constants determined from measurements. $\beta$ is the coefficient of thermal expansion and $l$ is the turbulent length scale which is diagnostically calculated every time step (e.g. Enger et al., 1993).
The first term on the right hand side of equation (20) is turbulent transport forces (Andrén 1990), the second is the shear-production, the third buoyancy production and the fourth dissipation. For a more detailed description of the model see for example Tjernström (1987).

2.2.2. The model setup for the Bora simulations

Different numerical methods are used to solve the equations in the model, for example a forward-in-time-upstream-in-space scheme to solve the advection equations (see Tjernström 1987). A vertically expanding grid is used, with high resolution near the ground, decreasing with height. The model area is showed in figure 1. Grid points in the vertical (z-direction) are 31 (model top = 10 km, Δz_{min} = 3 m, Δz_{max} = 417 m), in x-direction 35 (200 km, Δx_{min} = 1500 m, Δx_{max} = 16675 m) and in y-direction 21 (120 km, Δy_{min} = 3000 m, Δy_{max} = 11428 m). The time step used for this simulation is 15 seconds. A sponge layer is sited at 6100 meters and all eventual clouds are disregarded. Variables possible to change are: land temperature (T_{land}), sea temperature (T_{sea}), stratification (potential temperature = θ, and specific humidity = q) and wind (speed and direction). Each model simulation is executed for 30 hours, starting 19.00 LST the day before the one to be analysed.

![Figure 1. Model area for bora simulations. Northeastern part of the Adriatic Sea.](image)

3. Description of the bora wind

The most necessary condition to get bora at the eastern shore of the Adriatic Sea, is the approach of cold air from the northeast, always in association with a cold air outbreak in the Alpine area. When a cold front passes over the Alps, the lower part of the cold air is blocked, and then steered around the Alps and reaches the area around Zagreb from northeast. The cold air will then be trapped beneath an inversion layer. A strong pressure
The bora onset is characterised by a sudden drop of relative humidity, a decrease in temperature and an increase of pressure. Inside the bora layer, the wind blows normal to the barrier, from northeast, but above this layer the wind direction is often perpendicular or even opposite. Vertical wind profiles show a maximum in wind speed at approximately 1 km height, with rapidly decreasing wind speeds above. The bora will blow as long as there is a supply of cold air in northeast, and when this starts to lack the wind will decrease, but it will continue to blow until the supply is completely exhausted. Bora is more common at the northern part of the Adriatic coast than in the southern, and therefore this bora has been better investigated, but Jurčec and Visković (1994), for example, have analysed the bora in southern Adriatic. The strongest bora is located in the vicinity of Senj, due to the Vratnik Pass, where channelling effects play an important role. The height of the mountains here is only around 700 m, compared to 1100 m in northern direction and 1700 m in the southern. The most frequent bora is developed where the mountains are narrow and close to the coast, as in Split.

The bora is often classified into two different types:

**Cyclonic bora:** Also called "dark" bora, associated with cloudy sky and precipitation. It is characterised by a deep surface cyclone over southern Adriatic, and a pronounced upper-level trough. This type of bora blows steadily and often covers the entire Adriatic Sea. The depth is approximately 1 km and is considered as a shallow bora.

**Anticyclonic bora:** Also called "clear" bora, since the sky is often clear. This type of bora develops when the cyclone is further to the east of the Adriatic Sea than in the cyclonic bora, and often a cut off low is sited above the bora layer. A strong high pressure area must exist, with an extension of high pressure over Dalmatia, e.g. the Siberian anticyclone in the winter. This type of bora exhibits a violent character, but does not extend far out to sea, even if it may extent up to 3 km in depth.

### 4. The ALPEX-project

One of the projects in GARP (Global Atmospheric Research Program) was the ALPEX-project (Alpine Experiment), with participants from all over the world.

**4.1. The ALPEX-SOP**

The ALPEX-SOP (Special Observing Period) took place in March and April 1982. The scientific tasks were defined as (WMO 81):
- To determine the characteristics, under various synoptic conditions, of the air flow and the mass and moisture field over and around the Alpine mountain complex.
- To study the physical processes leading to the formation of cyclones in the lee of the Alpine mountain barrier, and the mechanism of their further development, with special emphasis on the sub-synoptic nature of the associated processes.
- To determine:
  - the drag of a mountain complex upon the atmosphere,
  - the vertical transport of horizontal momentum as a function of the height near a mountain range, and
  - the dissipation of gravity-inertial wave energy over and downhill of the mountain range.
- To study mountain winds (such as föhn, bora, mistral) and possible effects of mountains.
- To study the role of sensible and latent heat flux over the Mediterranean Sea and its significance in lee cyclogenesis.
- To study the effects of differential radiative heating introduced by the Alpine mountain range due to elevation, topographic features and albedo.
- To study the effect of mountain complex on precipitation.
- To investigate the physical processes responsible for the development of severe floods, winds and storm surges in the region of the Alps in order to improve their prediction.

A composition of upper-air stations, ships, aircraft, satellites, balloons, radar, etc. was used during the SOP.

4.2. Results from the bora observations

Before the ALPEX-SOP no aircraft observations of the bora had been made, so many questions about the bora waited to be answered. During the SOP in 1982 four periods with bora occurred: 5-7 March, 21-25 March, 13-16 April, and 27-30 April. On five of those days, flight observations were performed, see figure 2 for flight tracks. The results show that in all five cases the wind accelerates where the mountains begin to rise, which contradicts the idea of bora as a pure fall wind. Downstream the crest, over sea, an area of lesser stability and lower winds than in the incoming flow were found. A highly turbulent zone, shear driven, was found above the ridge crest. Only two of the days with flight observations, 22 March and 15 April, will be further discussed here, but a complete analysis of the other days can be found in Smith (1987).
4.2.1. 22 March 1982

This day was the second day in this bora period which lasted between 21 and 25 March. A cold front passed over central Europe from northwest a few days earlier and caused an outbreak of cold air in the Alpine region. The weather situation on the 22 March (figure 3) reveals a low pressure just south of Italy and a high pressure area further to the west. According to Smith (1987) the clouds were scattered in the area this day.

The flight observations this day took place about 40 hours after the bora onset and the flight started in Zagreb and went over Senj and Rab, see figure 2 (flight track P322). Measurements were performed at four levels between 13.58 and 16.14 GMT. This day, measurements in three dimensions were also performed at three different levels. The depth of this bora was 3.7 km in Zagreb.
A cross section of the wind measurements, in southwest-northeast direction, is showed in figure 4. The wind accelerates where the mountains begin to rise, over Karlovac, and reaches a maximum just above the ridge crest (22 m/s). Above the bora layer, indicated with a dotted line, the wind is weaker and the wind direction is northwesterly, compared to southwesterly inside the bora layer. The three dimensional flight reveals a highest wind speeds in the northwestern part of the area. The turbulence measurements in figure 5, shows strongest turbulence just above the ridge crest. It was also higher by the coast than over sea.

![Figure 4. Wind cross section for measurements on 22 March 1982. Dotted line indicates depth of bora. After Smith (1987).](image)

A strong inversion between 3 and 4 km (see figure 6) is developed in the incoming flow. This stability decreases when the air has past the crest, since the isotherms splits and decreases. The water vapour mixing ratio in figure 7 shows similar results. In figure 7 the vertical velocity is also showed.
Figure 6. Potential temperature cross section for measurements on 22 March 1982. The strong inversion in the incoming flow decreases downstream the crest. After Smith (1987).

Figure 7. Water vapour mixing ratio cross section for measurements on 22 March 1982. This measurement shows similar results to figure 6. After Smith (1987).

4.2.2. 15 April 1982

During this bora period, which lasted between 13 and 16 April only one day was observed with aircraft, namely 15 April. This bora period was the longest during the ALPEX-SOP with 138 h and a maximum gust of 44 m/s, observed on 14 April on Tito’s Bridge connecting Krk Island to the coast (Vučetić 1988). The bora onset was accompanied by a sudden drop of relative humidity, decrease in temperature and increase of pressure and wind speed (in Senj 10 m/s during 4 hours). An airstream around the eastern Alps caused a mesocyclone to form in the middle of the Adriatic sea, and the bora on 14 April should be classified as cyclonic. On 15 April the mesocyclone was filled out and an anticyclone over central Europe was intensified. Therefore, the bora on 15 April should be classified as anticyclonic. The weather situation for this day, when the bora was already in a decaying stage at most places, is showed in figure 8. The clouds
consisted of dissipating stratus and roll clouds downstream the crest (Smith 1987). This was a more shallow bora than the one on 22 March, extending only to 1.9 km at Zagreb.

Two ordinary flight observations were performed on 15 April, the first over the island of Krk between 8.29 and 9.36 GMT, and the second over Senj between 11.26 and 12.54 GMT, see figure 2 for flight tracks (P415). A third flight between 9.37 and 11.16 GMT observed wind and turbulence in three dimensions.

The flight over Senj, which was only inside the bora layer downstream, recorded wind speeds up to 22 m/s (see figure 9). The flight over Krk, recorded only 13 m/s. Both flights reveals a change in wind direction from easterly to southerly wind between 2 and 3 km, and as showed in figure 10 a strong inversion is sited at this height. This stability decreases downstream in a similar way to the inversion on 22 March.
The highest intensity of turbulence is located near the coast, and as earlier, just above the ridge crest (figure 11). In the flight over Krk a secondary turbulence maximum was observed over sea between the island of Cres and Krk. The water vapour mixing ratio is showed in figure 12. A moist layer is located downstream, between 1.5 and 2.5 km. The isolines decreases downstream in a similar way to the isotherms in figure 10. The moist layer is responsible for the roll clouds observed this day.
5. Simulations and results

Bora simulations were performed for two days, 22 March and 15 April 1982. These days were chosen due to the fact that neither of the days were very cloudy. On 22 March the clouds were scattered and on 15 April they consisted of dissipating stratus and roll clouds downstream. The two days are somewhat different, the bora on 22 March were deeper than the one on 15 April, 3.7 km compared to 1.9 km (measured at Zagreb). On 15 April the bora was already in a decaying stage at most places, while for the 22 March it was still blowing steadily. The stratification and wind was also different, see each section. The land temperature ($T_{\text{land}}$) used in the simulations were taken from hourly values from Zagreb, the initial stratifications from measurements during the ALPEX-SOP (Smith 1987) and the initial wind data was determined from weather maps (Europäischer Wetterbericht) and radio soundings, made at Zagreb, 12.00 GMT each day.

5.1. 22 March 1982

Maximum temperature in Zagreb this day was 6.8°C and minimum 1.7°C. Sea temperature used for the simulations this day was 9.3°C and the initial wind was kept constant at all levels, both in direction (northeast) and speed (12 m/s). The used stratification is listed in table 1, with a neutral layer up to 2000 m, and then a stable layer up to the model top (10000 m). The strongest inversion is sited between 3000 and 4000 m.
Table 1. Stratification used for simulation of the bora on 22 March 1982.

<table>
<thead>
<tr>
<th>$z$ (m)</th>
<th>$q$ (kg/kg)</th>
<th>$\theta$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>$0.7 \cdot 10^{-4}$</td>
<td>316</td>
</tr>
<tr>
<td>4000</td>
<td>$1.0 \cdot 10^{-4}$</td>
<td>292</td>
</tr>
<tr>
<td>3000</td>
<td>$1.0 \cdot 10^{-3}$</td>
<td>282</td>
</tr>
<tr>
<td>2000</td>
<td>$1.5 \cdot 10^{-3}$</td>
<td>280</td>
</tr>
<tr>
<td>1000</td>
<td>$2.0 \cdot 10^{-3}$</td>
<td>280</td>
</tr>
<tr>
<td>0</td>
<td>$2.5 \cdot 10^{-3}$</td>
<td>280</td>
</tr>
</tbody>
</table>

The numerical results show that the coastline has the highest wind speeds in the area, and at a place just north of Senj, near the coast ($y = 57 \text{ km}$, $x = 110 \text{ km}$, see figure 1), the wind speed reaches a maximum during the afternoon with 14 m/s at approximately 1 km height, see figure 13. The wind direction at this place changes only slightly with time, up to 2500 m the wind is from east-northeast, mostly due to channelling effects at the Vratnik Pass, and above 2500 m the wind direction is north-northeast. Over sea the wind direction is north-northeast at all levels and there is hardly no change with time.

![Wind speed map](image)

**Figure 13.** Simulated wind speed change with time at a place just north of Senj, 22 March. The strongest wind is in the afternoon, 14 m/s at approximately 1 km height.

In figure 14 the change in time of wind speed variance in $z$-direction is showed. It increases a little during the day, due to increased solar heating, but there are no big changes.
The specific humidity changes only with time at the lowest altitudes (up to approximately 500 m), and in the afternoon it increases a little, see figure 15.

The potential temperature does not change much with time at altitudes above 2000 meters, see figure 16. At lower altitudes (up to approximately 1 km), it decreases some in the night and in the afternoon. Over sea, there is only slight changes with time.
A cross section of the wind speed in west-east direction (y = 54 km, see figure 1), figure 17, shows a maximum just above the ridge crest, 14 m/s. The time is 15.00 GMT and the wind has accelerated from 12 m/s, which was the input. The highest wind speed at this time is found a little further to the north (y ≈ 70 km). This cross section can be compared to figure 4, but in figure 4 the cross section is in southwest-northeast direction. In both figures the wind reaches a maximum just above the ridge crest, but the simulated wind speed is not as high as the measured wind speed, 14 m/s compared to 22 m/s. The wind direction in the simulated case is east-northeast at the ridge crest, where the maximum wind speed was found, and then it veers to north-northeast above. The incoming flow (wind direction north-northeast) is steered through the Vratnik Pass and changes direction to northeast and then back to north-northeast over sea. It is only the wind in the lowest levels that is influenced by this channelling effect, at higher altitudes, the wind direction is unchanged, as for the wind direction north and south of the Pass. This corresponds well to the measurements, but the measurements shows a wind veer above the bora layer which can not be seen in the simulations.

Figure 17. West-east cross section (y = 54 km) for simulated wind speed at 15.00 GMT, 22 March. The wind has accelerated from 12 m/s to 14 m/s. Wind direction is east-northeast at the crest and north-northeast above.
The cross section for wind speed variance in the z-direction, figure 18, shows higher values over sea than over land, because the sea is relatively warm, and there is no maximum at the ridge crest as there is in figure 5.

In figure 19, the cross section for potential temperature is displayed. The isotherms descend downstream the crest, which also can be seen in figure 6, but the strong inversion, measured at 3 km, is weaker in the simulated case (notice the different scales). The stability in the northern part of the area is also stronger than in the southern part because the mountains are higher in the north than in the south, and since the wind direction is north-northeast the isotherms descend in a similar way to figure 19. The weaker stability in the simulated case is one of the reasons for the lower wind speeds, and the weaker stability is a consequence of the resolution in the z-direction.
The specific humidity in figure 20 has its highest values over sea and the isolines descends downstream in a similar way to the isotherms in figure 19. Compared to figure 7 the values are a little to high, but otherwise it shows the same pattern.

![Specific humidity graph](image)

**Figure 20.** West-east cross section for simulated specific humidity at 15.00 GMT, 22 March. The isolines descends downstream in a similar way to figure 19.

Figure 21 displays the simulated vertical velocity with an upward motion just behind the ridge crest. Further to the north, it shows a little higher wind speeds, but the direction of the motion is the same. Compared to the measurements in figure 7 this corresponds well.

![Vertical velocity graph](image)

**Figure 21.** West-east cross section for simulated vertical velocity at 15.00 GMT, 22 March.

### 5.2. 15 April 1982

In the simulation this day, the wind was kept constant up to 1500 m, with 5 m/s and the wind direction was east-northeast. Above 1500 m the wind veers clockwise and decreases in speed and at 5000 m the wind speed is 2 m/s, wind direction south-southwest.
From 5000 m and up to the model top, the wind was kept constant again with 2 m/s, wind direction south-southwest. Maximum temperature in Zagreb this day was 10.0°C and minimum 2.2°C. Sea temperature used was 9.6°C, and the stratification as in table 2, with the strongest inversion between 1500 and 3000 m.

Table 2. Stratification used for simulation of the bora on 15 April 1982.

<table>
<thead>
<tr>
<th>z (m)</th>
<th>q (kg/kg)</th>
<th>θ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.5·10⁻⁴</td>
<td>316</td>
</tr>
<tr>
<td>4500</td>
<td>1.0·10⁻³</td>
<td>304</td>
</tr>
<tr>
<td>3100</td>
<td>3.0·10⁻³</td>
<td>302</td>
</tr>
<tr>
<td>2900</td>
<td>4.0·10⁻³</td>
<td>300</td>
</tr>
<tr>
<td>2500</td>
<td>4.0·10⁻³</td>
<td>298</td>
</tr>
<tr>
<td>2300</td>
<td>4.0·10⁻³</td>
<td>296</td>
</tr>
<tr>
<td>2200</td>
<td>3.5·10⁻³</td>
<td>294</td>
</tr>
<tr>
<td>2100</td>
<td>3.1·10⁻³</td>
<td>292</td>
</tr>
<tr>
<td>2000</td>
<td>3.0·10⁻³</td>
<td>290</td>
</tr>
<tr>
<td>1900</td>
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<td>288</td>
</tr>
<tr>
<td>1700</td>
<td>2.0·10⁻³</td>
<td>286</td>
</tr>
<tr>
<td>1500</td>
<td>3.0·10⁻³</td>
<td>284</td>
</tr>
<tr>
<td>0</td>
<td>3.0·10⁻³</td>
<td>282</td>
</tr>
</tbody>
</table>

The numerical results show that the wind speed increases with time and reaches a maximum during the afternoon (22 m/s), see figure 22 (same place as for 22 March). Above this maximum, the wind speed decreases rapidly. The simulations also show that the wind speed is highest near the coast. The wind direction is northeasterly up to approximately 2 km and does not change much with time. Between 2 and 3 km it changes during the day, it veers from east-northeast to southeast and then back to east-northeast. One explanation for this is the gravity waves created by the ridge. The change in wind direction can also be noticed over sea, but the change is not as big as at the coast. Above 3 km, the wind direction is southerly both at the coast and over sea, and there are no big changes with time.

Figure 22. Simulated wind speed change with time at a place just north of Senj, 15 April. The wind speed reaches a maximum in the afternoon with 22 m/s. Wind direction is northeasterly up to 2 km and between 2 and 3 km it changes during the day. Above 3 km the wind direction is southerly.
The wind speed variance in z-direction shows a maximum in the morning, between 1 and 3 km, see figure 23. This maximum can only be seen near the coast just north of Senj at this time of the day. In the afternoon, another maximum was developed, but this time further to the south, which is one evidence that the bora changes its character all the time, and consequently also the turbulence changes.

Figure 23. Simulated change in wind speed variance in the z-direction with time. Same places in figure 22, 15 April. A maximum in the morning between 1 and 3 km can be noticed.

In figure 24, the change in specific humidity with time is displayed. The isolines decrease some with time and at approximately 2 km height a minimum is reached in the morning. Near the surface, the specific humidity increases slightly during the day.

Figure 24. Simulated change in specific humidity with time. Same place as in figure 22, 15 April. The isolines decreases some with time.
The change in potential temperature with time is showed in figure 25. The strongest stability during the night is sited between 2 and 3 km. During the day, on the other hand, this nocturnal stable layer decreases from below, due to increased solar radiation, and the stability becomes the same at all levels. Notice the different scale compared to 22 March.

![Figure 25. Simulated change in potential temperature with time. Same place as in figure 22. 15 April. The stability between 2 and 3 km at night decreases some during the day.](image)

A cross section of the wind speed simulations in west-east direction is displayed in figure 26 (time 12.00 GMT, y = 57 km, see figure 1). The strongest maximum is sited just behind the ridge crest with 20 m/s. Another maximum with 16 m/s can be found above the first island (Krk). Above these maximum, the wind speed decreases rapidly. The wind has accelerated from 5 m/s which was the input (up to 1500 m). The wind direction is easterly at the ridge crest and then it veers to south at approximately 3 km height. Over sea, the wind direction is east-northeast up to 3 km, and then it veers in the same way as at the crest. The strongest wind speed in the area is found at the coast and especially near the Vratnik Pass (22 m/s). The cross section corresponds to figure 9, with the difference that figure 9 is in southwest-northeast direction. In both measurements and simulations the maximum wind speed is sited just behind the ridge crest. The simulated case has a maximum wind speed of 20 m/s and that is about the same as the measured maximum wind speed (22 m/s). Above this maximum the wind speed decreases rapidly both in simulations and measurements. The wind direction is easterly up to 3 km in the simulations; no measurements were made below 2 km so nothing can be said about the wind there, but at 2.5 km the measured wind direction was southerly. The second flight performed this day (over Krk) reveals a wind veer between 2 and 3 km.

23
The west-east cross section for simulated potential temperature is displayed in figure 27. The isotherms descend after passing the ridge crest and the upstream stability decreases and, as for 22 March, the stability is stronger in the northern part of the area. The descents of the isotherms correspond well to the measurements, figure 16, but as for 22 March, the upstream stability in the measurements is stronger than in the simulations.
In figure 28 the west-east cross section of wind speed variance in z-direction is showed. The maximum mentioned earlier, the one in the morning, can not be seen at this time, there is just a small increase at the ridge crest, but further to the south there is a maximum at the ridge crest, which corresponds well to the measurements in figure 11.

The cross section for simulated specific humidity is displayed in figure 29, with its highest values above sea. The isolines descends downstream the crest in a similar way to the isotherms in figure 27. The measured maximum (the moist layer) in figure 12 can not be seen in the simulations, mostly due to the limited resolution and the fact that the clouds this day were disregarded in the simulations.
The simulated vertical velocity is showed in figure 30. As for 22 March, it is positive just behind the ridge crest and a little stronger in the northern part of the area than in the southern. This upward motion was also recorded in the measurements, figure 12.

![Simulated vertical velocity](image)

**Figure 30. West-east cross section for simulated vertical velocity at 15.00 GMT, 15 April.**

### 5.3. Discussion of the results

The simulation of the bora on 22 March was very sensitive to changes in the input variables. Only a small change in wind speed or wind direction, gave a completely different result. This supports the idea that the bora is not a pure fall wind, but rather a combination between the approach of cold air in the lowest layers and specific synoptic situations. There is a large margin of error in the input, especially in the wind data, which is one of the reasons for the differences between the simulations and the measurements. Another explanation for the lower wind speeds is that the upstream inversion in the simulations was not as strong as in the measurements. The number of grid points in the vertical limits the resolution and consequently also the strength of the inversion. The sea temperature used for this simulation (9.3°C, received from Zagreb) was relatively warm compared to the land temperature this day (max. 6.8°C at Zagreb), and therefore the turbulence is highest over sea.

The bora on 15 April was easier to simulate than the one on 22 March, mostly due to the fact that the bora on 15 April was shallower, and since the used model is developed for mesoscale studies, it works better with smaller scales (on the mesoscale). This simulation is a good example to that the bora changes its structure all the time, and that it is a function of both time and space; the turbulence shows two maximum at the ridge crest, but at different places and different times. In a similar way to 22 March, the resolution for
potential temperature and specific humidity is not as good in the simulations as in the measurements. Another reason for the abscess of the moist layer in the simulations, which was found in the measurements is the fact that all clouds were disregarded in the simulations, and since the moist layer is responsible for the roll clouds downstream the crest this day, this can not be correctly simulated.

The numerical results shows that three dimensional effects, for example channelling effects, is important for the bora structure. The fact that the wind speed is highest near the coast at the Vratnik Pass, in one consequence of that the flow at lower altitudes is steered through the Pass, and that the wind direction is different than at higher altitudes above the Pass.

Compared to measurements, the model simulates the two days well, especially on 15 April when the bora was relatively shallow. All the significant features of the bora wind were well simulated, the wind speed maximum at the ridge crest, the descent of isotherms and isolines of specific humidity downstream the crest, channelling effects etc. The turbulence was not always present just above the ridge crest, but at some times and some places it was well simulated. The most difficult variables to simulate was the specific humidity and the potential temperature. The main problem here, is the resolution in the z-direction and to get better results the number of grid points has to be increased, but as always the number of grid points must to be optimised with the computer time.

One of the largest problem with this study of the bora wind was to determine correct input variables. Especially the wind, which was determined from weather maps and consequently this has a large margin of error in both speed and direction. To get better results this is the first thing that should be improved.

6. Conclusions and summary

The eastern shore of the Adriatic Sea, between Trieste in north and Dubrovnik in south, is affected by the bora wind. The bora is a cold, dry and gusty downslope wind and gusts above 50 m/s is not unusual. The bora has often been classified as a pure fall wind, which accelerates due to its low temperature and greater density as it moves downslope, but as this study shows, it is rather a combination between the approach of cold air from northeast and specific synoptic situations. In the ALPEX-project 1982, the first aircraft measurements of the bora was performed, and results from this project also supports the idea that the bora is not a pure fall wind. Many attempts to numerically simulate flow over mountains have been made earlier, but most of these were made in two dimensions.

Flow over mountains causes vertically propagating waves, and the Froude number (the ratio between inertial force and buoyancy force) play an important role. If Fr = 1 at the ridge crest, the flow will become supercritical (Fr < 1) and continue to accelerate as it
descends the lee side until it adjusts back to subcritical flow \((Fr > 1)\) in a hydraulic jump. In this case very high velocities can occur along the lee slope since potential energy is converted into kinetic energy while the flow passes the barrier. This theory is most important for air flow in two dimensions. Unfortunately, there is no general theory for three dimensional mountain gravity waves, which play an important role for the development of bora. Thus, we proceed with numerical modelling.

This work have showed an numerical analysis of the bora wind in three dimensions. The model used for the simulations was a three dimensional, hydrostatic mesoscale model developed at Department of Meteorology, Uppsala University. Two case studies were made, for 22 Mach and 15 April 1982, and the results were compared to measurements performed during the ALPEX-SOP in 1982. The bora on 15 April was shallower than the one on 22 March and therefore it was much easier to simulate, since the model is developed for mesoscale studies.

The bora is known to change structure all the time, and the numerical results in this study supports this. One example of this is the simulation of turbulence on 15 April, where a turbulence maximum, sited at the ridge crest is a function of both time and space. Three dimensional effects plays an important role, for example channelling effects at the Vratnik Pass, where the highest wind speeds along the coast often are recorded, and this was also the case in this simulation.

Compared to measurements, the model simulates the two days well, especially 15 April. All the significant features of the bora wind were well simulated, the wind speed maximum at the ridge crest, the descent of isotherms and isolines of specific humidity downstream the crest, channelling effects etc. The turbulence was not always present just above the ridge crest, but at some times and some places it was well simulated. The most difficult variables to simulate was the specific humidity and the potential temperature. The main problem here is the resolution in the z-direction and to get better results the number of grid points has to be increased, but as always, the number of grid points must to be optimised with the computer time.

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7. References


