A preliminary numerical simulation of bora wind with a limited area model of atmospheric circulation

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Summary. — One case of bora that burst out on the 4th of January 1995 has been simulated with a regional atmospheric model (RAMS). This was a typical bora with a stationary cyclone that remained over southern Adriatic Sea during the whole episode of bora. Some common features of bora such as upstream acceleration, strong descent within bora layer and turbulent zone just downstream of the mountain have been demonstrated by the model simulation. The simulation of the bora wind speed and direction showed good agreement with the observation in Trieste (Italy).

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1. – Introduction

Bora has been studied by scientists for more than one hundred years. The earliest studies on bora were mostly descriptive. Bora was described as a cold and dry wind that was highly influenced by the local topography [1-3]. Later, some special field observations and wind tunnel experiments were performed and since then bora started to be considered as a fall wind [4]. However, the idea that the bora is a "fall wind" was questioned after the aircraft observation (ALPEX Project) carried out in 1982, by the fact that the wind accelerates where the mountain slopes upward. This evidence suggested that bora might be the "downslope winds" like the well-known Boulder windstorm [5]. The shallow water dynamics briefly explains the downslope winds in terms of Froude number (Fr). When the far-upstream bora flow is presumed to be subcritical ($\mathrm{Fr} < 1.0$), then around the top of the ridge its Froude number gets near 1.0,

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and furthermore the bora flow becomes supercritical ($\mathrm{Fr} > 1.0$) on the lee side; under this circumstance the bora will be accelerated continuously until it returns to the subcritical state through a hydraulic jump [6, 7]. So the hydraulic theory was applied and the hydraulic model turned out to be partially successful to simulate bora.

Afterward, a multiscale nature of bora was suggested. The speed and direction of bora greatly depend on the topographic shape, so mountain and coastal circulations are clearly responsible for daily variation of wind speed and direction during bora period. However, in spite of these local effects, the bora onset, its longevity and severity are closely related to larger mesoscale features, in particular those resulting from the interaction processes of synoptic scale flow with the Alpine massif (Jurcec [8] and Branka Ivancan-Picek etc. [9]). Because of the multiscale nature of bora, the mesoscale atmospheric model might be an efficient model to simulate bora. In this preliminary work, the Regional Atmospheric Modeling System (RAMS) has been used to perform the study of bora by using a high-resolution topography data set (1 km × 1 km). One bora case, which burst out on the 4th of January 1995, has been simulated.

2. – The regional atmospheric model

RAMS, the Regional Atmospheric Modeling System, is a highly versatile numerical code for simulating and forecasting meteorological phenomena and is constructed around the full set of primitive dynamical equations which govern atmospheric motions. Users have the possibility to activate grid nesting option in order to have higher resolution for the region which they are interested in. In our present work, the nested grid, which is called the second grid, is deployed to cover the bora region. The mother grid of the second grid is usually called first grid. Users can nest the second grid again to get a third grid. But for our preliminary research we did not activate any third nest grid.

The supplements of these equations include optional parameterizations for turbulent diffusion, solar and terrestrial radiation, moist processes including the formation and interaction of clouds and precipitating liquid and iced hydrometeores, kinematic effects of terrain, and cumulus convection, sensible and latent heat exchange between the atmosphere, multiple soil layers, a vegetation canopy, and surface water.

The major parameters to be set in order to simulate the bora are:

1) Number of first grid points: 40 × 40 × 35
   Number of second grid points: 32 × 32 × 35
   Horizontal spacing for first grid: 50 km; second grid: 10 km
   Vertical grid spacing: 50 meters
   Stretch ratio 1.2 (until vertical grid spacing reaches 1000 meters).
2) First grid timestep: 90 seconds
   Second grid timestep ratio: 4.
3) Initial files: from ECMWF.
4) Lateral boundary condition: Klemp-Wilhelmson.
5) Parameterizations for turbulent diffusion: Horizontal deformation scheme; Vertical Mellor-Yamada scheme
   Parameterizations for radiation: Chen-Cotton (the effects of liquid and ice have been considered).

3. – Results

Since both local topography and weather features on mesoscale and synoptic scale (for instance, cyclonic activity in South Adriatic Sea) can influence the bora, the domain of our simulation covered the whole alpine mountain range, the western Mediterranean Sea and Adriatic Sea, so extending as far as 2000 × 2000 km^2. Figure 1 shows the topography contours of our simulation domain.

In fig. 1, the top of vertical topography features can reach the maximum height of only 2800 meters. Although our data set of the topography is 1.0 × 1.0 km, the model resolution of the first grid is 50 km. Some highest mountain peaks are not captured.

The bora case that we have simulated is a typical one with a stationary cyclone which remained over the South Adriatic Sea during the whole bora episode. Figure 2 shows the simulated 850 mb geopotential height at the strongest time of development of bora (12:00 a.m. 4th January 1995). This cyclone formed early in the morning of 3rd January and lasted almost 3 days.

The resolution of our second nested domain is 10 km centered over Trieste. Figure 3 shows the domain of our second nested grid, which covered the bora region. Figure 3 also shows the simulated wind field at the strongest moment of bora that we have analysed (12:00am 4th January 1995). The wind reached as far as 20 m/s near the surface inland. There are two strong wind zones over the Adriatic Sea on both sides of the Istria Peninsula. We have already noticed that even if bora varies considerably from case to case, nevertheless several common features (such as upstream acceleration, strong descent within bora layer and turbulent zone just downstream of

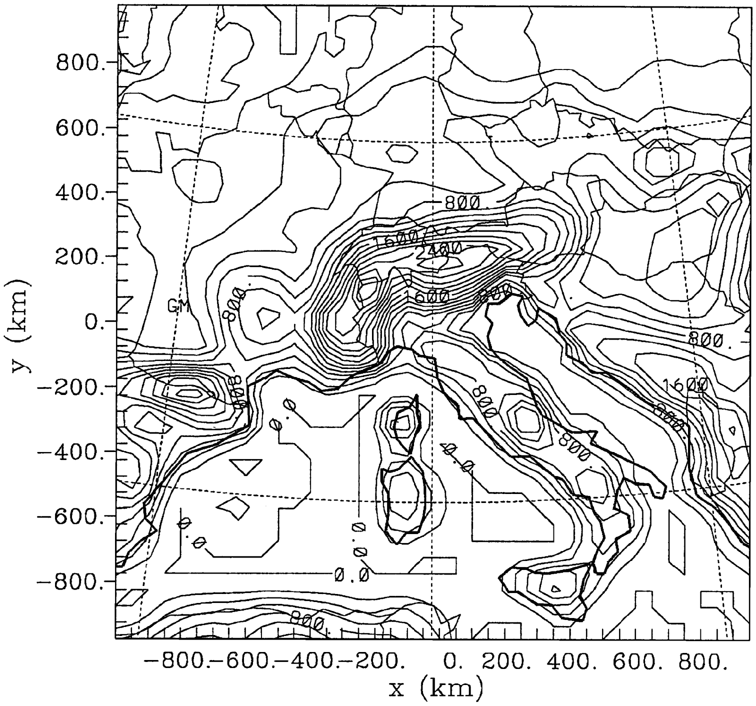

Fig. 1. – Topography of simulation domain (m).

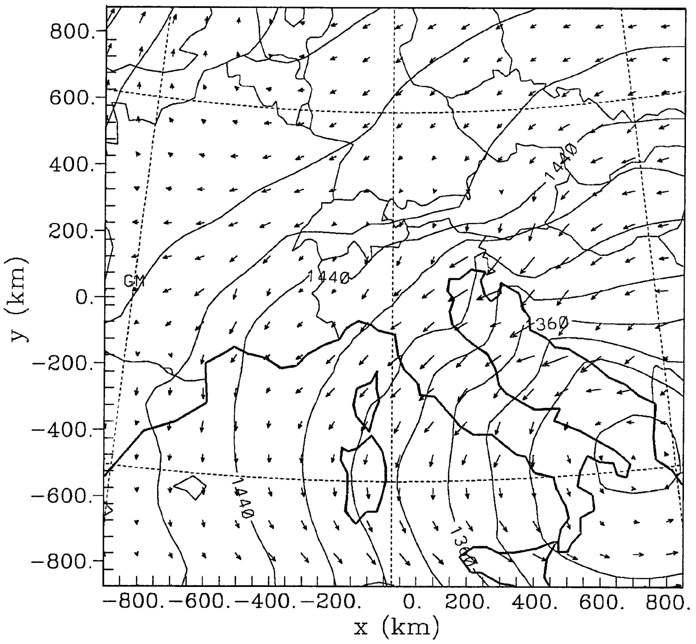

Fig. 2. – Simulated 850 mb geopotential height (m) at the strongest moment of bora (12:00am 4/01/1995).

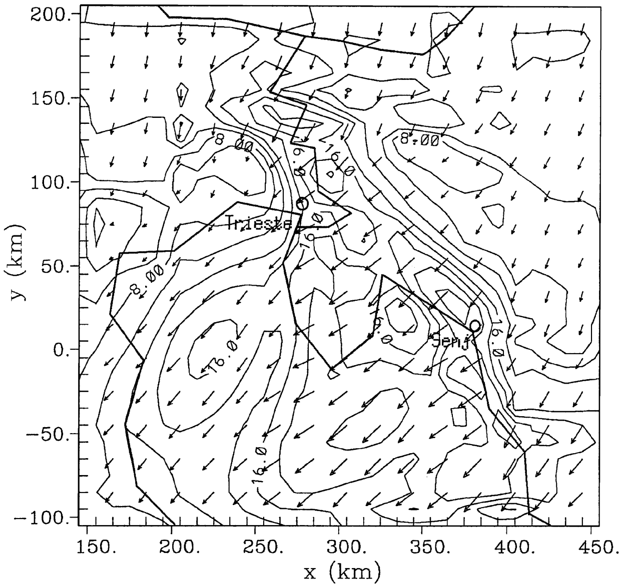

Fig. 3. – Simulated surface wind field (m/s) at the strongest moment of bora (12:00am 4/01/1995).

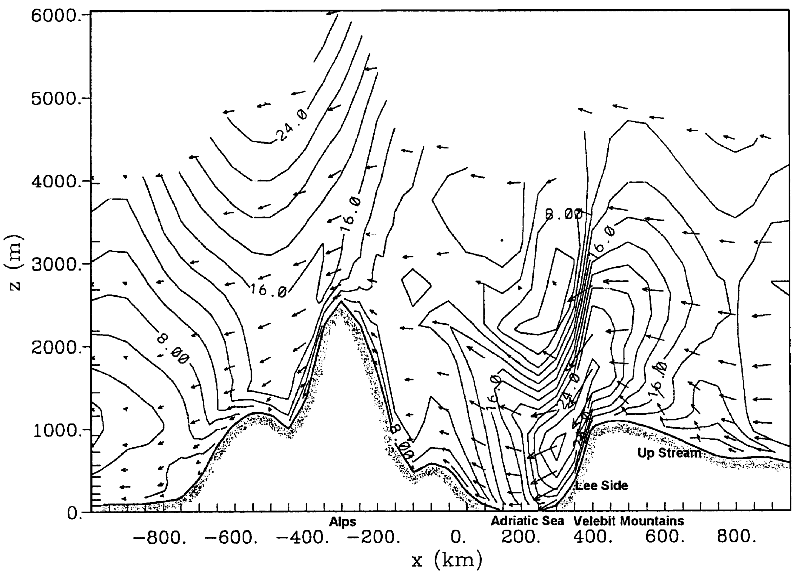

Fig. 4. – Simulated vertical section of wind vector field and isolines of wind speed (m/s) at the strongest moment of bora (12:00am 4/01/1995).

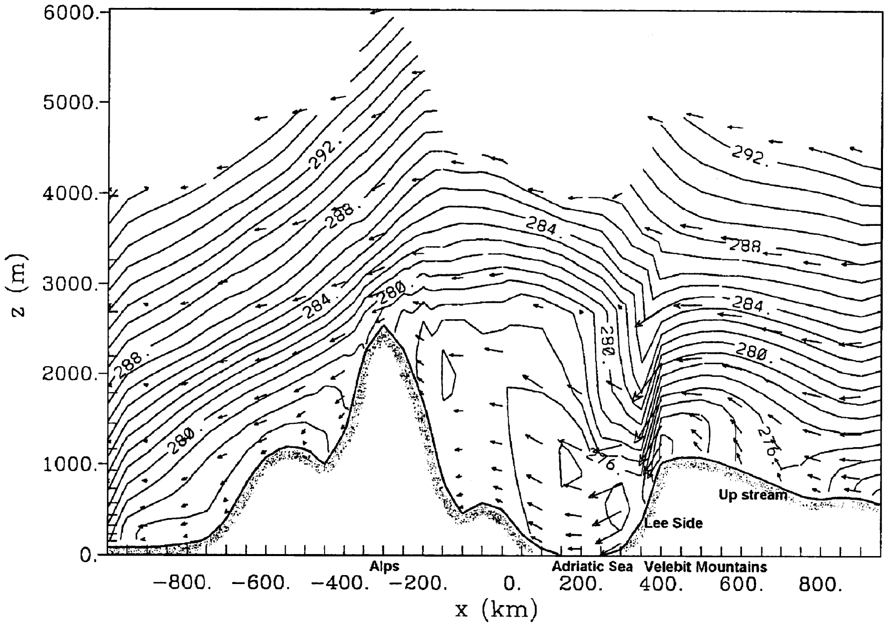

Fig. 5. – Simulated vertical section of isolines of potential temperature (K) and wind vectors at the strongest moment of bora (12:00am 4/01/1995).

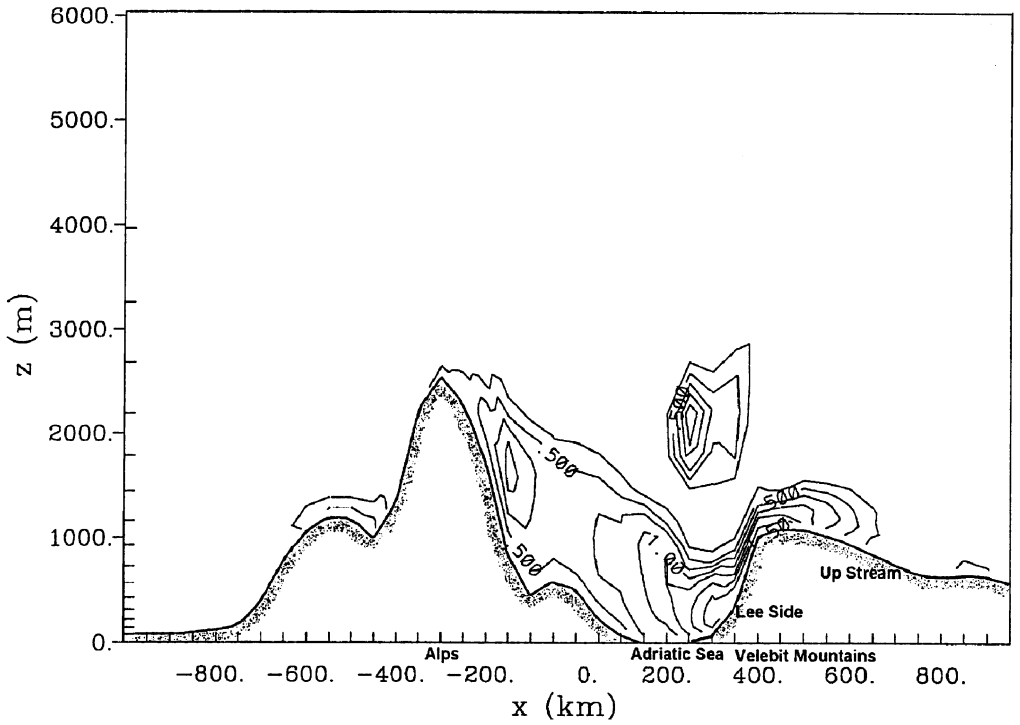

Fig. 6. – Simulated vertical turbulence kinetic energy (m^2/s^2) section at the strongest moment of bora (12:00am 4/01/1995).

the mountain) are evident. The continuation of this section will present and discuss these common features of the bora wind, as they emerged from our model simulation which demonstrate the good reliability of our simulation. The results of our simulation have been also compared with direct observation data in Trieste, provided by the Istituto Sperimentale Talassografico di Trieste of CNR (see subsect. 3˙4).

3˙1. *Upstream acceleration.* – The upstream acceleration within the bora layer was observed first in 1982, during the ALPEX Project. The acceleration began approximately where the mountain's slopes started to rise. This observation contradicts the simplest model of a "fall wind" entailing acceleration only when air is moving downslope. Our model simulates this upstream acceleration within the bora layer. Figure 4 shows an east-to-west section of simulated wind vectors and isotachs along the latitude 100 km south of Trieste. From this section where the ALPEX Project was carried out in 1982, the effect of Adriatic Sea on bora is will represented. In fig. 4, the wind vectors and isotachs clearly show the upstream acceleration (from + 400 km to + 600 km in the abscissa). Due to flight safety reasons, the aerial observation in 1982 only exhibited upstream acceleration 2 km above the sea level. Figure 4 shows this upstream acceleration even near the surface layer.

3˙2. *Strong descent below 2-3 km.* – Aerial observation during the ALPEX Project showed that the bora layer, whose depth is usually 2-3 km, exhibited strong descent just past the crest because of the steep cliff. Figure 5 shows an east-to-west vertical section of simulated potential temperature and wind vectors along the same latitude as in fig. 4. Of course, the potential temperature cannot represent the bora flow (only the equivalent potential temperature can). However, in this simulation, their patterns were similar, because dry conditions occurred. From fig. 5, the simulated potential temperature confirms the great descent in the lee side of the mountain (at around + 400 km in the abscissa). Above 3 km, the flow is still slightly disturbed, up to about 4 km.

The sharp downslope descent creates hydraulic jump in the lee side facing the Adriatic Sea. The wind slows down especially on the rear part of the bora layer, just after the jump. Shear-driven turbulence appears in this region.

3˙3. *The turbulence region.* – Aerial observation during the ALPEX Project showed that there was a turbulent zone just downstream of the mountains, 2 km above the surface. Our simulation also exhibits this turbulent zone (see fig. 6, + 300 km in the abscissa, 2 km above the surface). In fig. 6, the turbulent kinetic energy is of the order of 1.0 $\mathrm{m^2/s^2}$. But during the aerial observation, this value reached the order of 10.0 $\mathrm{m^2/s^2}$. This is probably due to the fact that the instrument designated to measure the vertical velocity could not separate between systematic velocities and turbulence in such a complex topography [5]. So the observation was likely to overestimate the turbulent kinetic energy. Nevertheless, the turbulent pattern of our simulation is quite similar to the observation.

3˙4. *Comparison with observation in Trieste.* – Besides successfully simulating the above-discussed common features of bora, our simulations of bora wind speed and direction showed a good agreement with the observation made in Trieste by the Istituto Sperimentale Talassografico di Trieste of CNR. Figures 7 and 8 show the comparisons of bora wind speed and direction starting from 00:00 of 2nd January 1995. The thick lines represent the simulation, while the thin lines are observations. The agreement of the comparison is quite good for this preliminary study. In fig. 7, the simulation of the velocity overestimates the observation a little. A reason for this

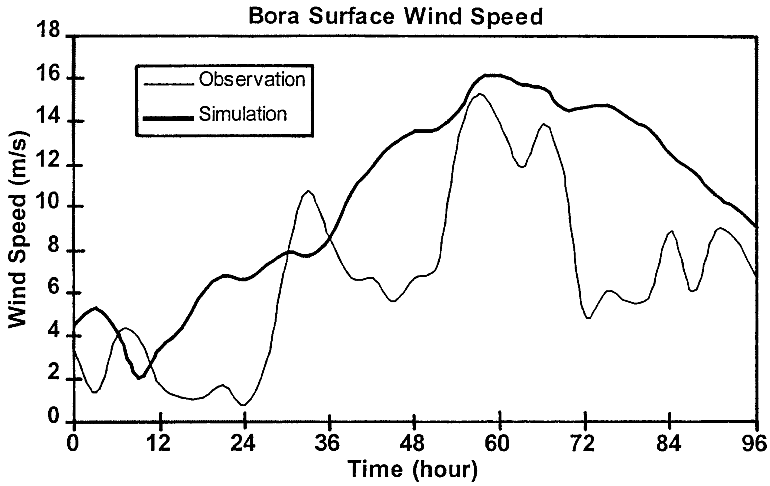

Fig. 7. – Comparison of surface wind velocity starting from 0:00 2nd January to 0:00 6th January 1995.

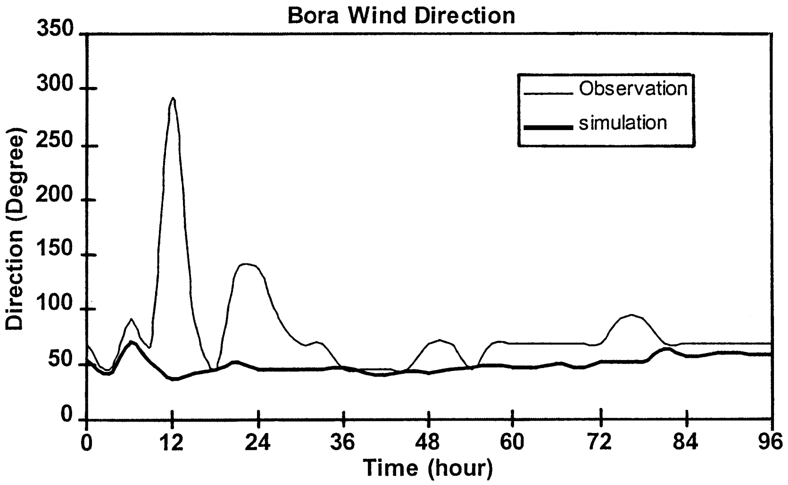

Fig. 8. – Comparison of surface wind direction starting from 0:00 2nd January to 0:00 6th January 1995.

overestimate is that the bora wind velocity and its direction are highly dependent on the local topography. At present, our finest grid of simulation is 10 km. This means that our simulation actually is the average value over 10 × 10 km^2. We can be confident that the agreement will be better when the resolution will be increased. But this will be next step of our research work. Nevertheless, the simulation peak of the wind speed coincides with the observation one. In fig. 8, the difference of wind direction between the simulation and observation is less than 20 degrees during the bora period.

4. – Conclusion

A preliminary model simulation of a bora episode occurred during the first week of January 1995 performed with a limited area model could capture all the common features of this particular wind such as upstream acceleration, strong descent within bora layer and turbulent zone just downstream of the mountains, which demonstrates the success of our simulation. From the direct comparison of wind direction and speed in Trieste which are strongly dependent on the topography complexity, the model gives quite a precise simulation.

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