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53

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# BORA IN REGIONAL CLIMATE MODELS: IMPACT OF MODEL RESOLUTION ON SIMULATIONS OF GAP WIND AND WAVE BREAKING

## Bura u regionalnim klimatskim modelima: utjecaj horizontalne rezolucije u modelu na simulacije kanaliziranih vjetrova i lomljenja valova

LUKAS JOSIPOVIĆ, ANIKA OBERMANN-HELLHUND,
ERWAN BRISSON and BODO AHRENS

Institute for Atmospheric and Environmental Sciences, Johann-Wolfgang-von-Goethe-University, Altenhöferallee 1, 60438, Frankfurt am Main, Germany

*lukas.josipovic@freenet.de*

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**Abstract:** Bora, a mesoscale wind system on the eastern Adriatic coast, profoundly impacts the local weather conditions. During easterly inflow, wave breaking generates heavy downslope winds in the lee of the Dinaric Alps. Additionally, gap winds emerge in canyons like the Vratnik Pass near Senj and enhance the Bora to a jet-like flow. The representation of these processes in numerical models is highly dependent on the surface description and therefore on model grid spacing.
This study evaluates two simulations with the regional climate model COSMO-CLM with grid spacing of 0.025° and 0.11° regarding Bora winds. Strong Bora events are discussed in detail using observations between December 1999 and November 2000. The model results show that a 0.025° high-resolution simulation can well reproduce both phenomena gap wind and wave breaking. The 0.11° simulation resolves gap winds surprisingly well but misses wave breaking events.

***Key words:*** Bora, wave breaking, gap winds, regional climate models

**Sažetak:** Bura je mezoskalni sustav vjetra na istočnoj obali Jadrana koji znatno utječe na lokalno vrijeme. Tijekom strujanja s istoka, kao posljedica lomljenja gravitacijskih valova, nastaje jak silazni vjetar na zapadnoj strani Dinarskih Alpa. Dodatno, vjetar se kanalizira u gorskim prijevojima poput Vratnika u blizini Senja te još više pojačava buru. Prikazivanje tih procesa u numeričkim modelima znatno ovisi o opisu tla te o horizontalnoj rezoluciji modela.
U ovom radu procjenjuju se dvije simulacije bure napravljene regionalnim klimatskim modelom COSMO-CLM s rezolucijom 0,025° i 0,11°. Pojava jake bure detaljno je razmatrana na temelju mjerenja vjetra u razdoblju od prosinca 1999. do studenog 2000. Rezultati modela pokazuju da simulacija s boljom rezolucijom od 0,025° može reproducirati i kanalizirani vjetar i lomljenje gravitacijskih valova. Simulacija modelom rezolucije 0,11° dobro pokazuje kanalizirani vjetar ali ne zahvaća lomljenje valova.

***Ključne riječi:*** bura, lomljenje gravitacijskih valova, kanalizirani vjetar, regionalni klimatski modeli

## 1. INTRODUCTION

Bora is a cold downslope wind occurring from Trieste (Italy) along the Croatian coast and down to the Montenegrin coast and usually blows from the Northeast. It develops by breaking of gravity waves due to occurrences of critical layers in the Dinaric Alps (Durran, 2003) and increases to a jet-like flow through canyons in the mountains like the Vratnik Pass near Senj (Grisogono and Belušić, 2009; Trošić and Trošić, 2010). Along the eastern Adriatic coast, Bora wind speeds higher than 40 $ms^{-1}$ occur regularly, leading to serious damage (Stiperski et al., 2012; Trošić and Trošić, 2010).

Due to the complex orography and processes involved, Global Climate Model (GCM) simulations or coarse-grid Regional Climate Model (RCM) simulations are unable to reproduce observed mesoscale wind phenomena like Bora. Obermann-Hellhund and Ahrens (2018) found that the limited orographic detail inherent to coarse resolution RCMs or GCMs leads to inaccurate wind pattern and wind speed during Mistral events. Several studies investigated Bora, for example, Kuzmić et al. (2015) who examined the differences between deep and shallow Bora, or Prtenjak et al. (2010) who analyzed the interaction of Bora and the sea-land breeze along the north-eastern Adriatic coast. Besides studying Bora in climate change scenarios (Belušić Vozila et al., 2018), Belušić et al. (2017) investigated small-scale wind systems on the Adriatic in simulations with the regional climate model COSMO-CLM (CLM-Community, 2017) with different spatial resolutions. They concluded that the grid distance of a simulation must be no more than a few kilometers to resolve wind systems, such as Bora, sufficiently. Here, we want to complement their study by specifically addressing gravity wave breaking and gap winds as these processes are the main generating mechanisms for Bora occurrence.

In this study, we discuss the representation of the small-scale Bora wind system in COSMO-CLM simulations. Is a grid-spacing of 0.11° as applied, for example, in the Coordinated Downscaling Experiment European Domain EURO-CORDEX (EURO-CORDEX, 2018) sufficient or is a higher resolution essential?

## 2. OBSERVATIONS, MODEL SIMULATIONS AND RELEVANT EVENTS

The observational datasets and model setup used in this study are described in this chapter.

### 2.1. Observations

The observations include hourly data from seven meteorological stations obtained from the NOAA National Centers for Environmental Information (NCEI, 2017). Table 1 contains further information on the weather stations, and Figure 1 gives an overview of the geographical position of the stations. For the wave breaking analysis, the meteorological stations Ogulin (O) and Gospić (G) in the luv of the Dinaric Alps, Rijeka/Krk (Rijeka Airport, R) and Zavižan (Z) in the lee were chosen for comparison. These stations surround an area with the length of 65 km from the island of Krk up to the Zavižan in the middle of one of the northern parts of Dinaric Alps, called Velebit. The stations in the luv are considered to show that high wind speeds in the lee during shallow Bora events are actually produced by a small-scale process at the mountains, and not by a synoptic-scale phenomenon.

Observations from the stations Senj (S) and Pula (P) were used for the investigation of the gap winds at the Vratnik Pass (V). The accuracy of wind speed and direction is 0.1 $ms^{-1}$ and 1°, respectively, at all stations. Some stations have data gaps, which explain the missing data in the figures below.

### 2.2. Model simulations

All simulations investigated in this study were performed using the Consortium for Small-scale Modelling in climate mode model (COSMO-CLM) in version COSMO5.0 CLM9. The COSMO-CLM model is a non-hydrostatic limited area climate model, based on the COSMO model (Steppeler et al., 2003), a model designed by the Deutscher Wetterdienst (DWD) and others for operational weather predictions. The Climate Limited-area Modelling Community (CLM) adapted this model to perform climate projections (Böhm et al., 2006, Rockel and Geyer, 2008).

Table 1. Weather station locations and model's next grid-point elevations. Positions relative to the Dinaric Alpes are also given.

Tablica 1. Lokacije meteoroloških postaja, nadmorske visine najbližih točaka modela i pozicija prema Dinarskim Alpama.

| Name | Lat. [° N] | Lon. [° E] | Elev. [m amsl] | | | Lee |
|---|---|---|---|---|---|---|
| | | | De facto | CCLM 0.025° | CCLM 0.11° | |
| Ogulin | 45.3 | 15.2 | 328 | 387 | 446 | No |
| Gospić | 44.6 | 15.4 | 565 | 558 | 699 | No |
| Rijeka / Krk | 45.2 | 14.6 | 85 | 26 | 39 | Yes |
| Zavižan | 44.8 | 15.0 | 1597 | 1317 | 777 | Yes |
| Senj | 45.0 | 14.9 | 85 | 117 | 195 | Yes |
| Pula | 44.9 | 13.9 | 32 | 76 | 22 | Yes |

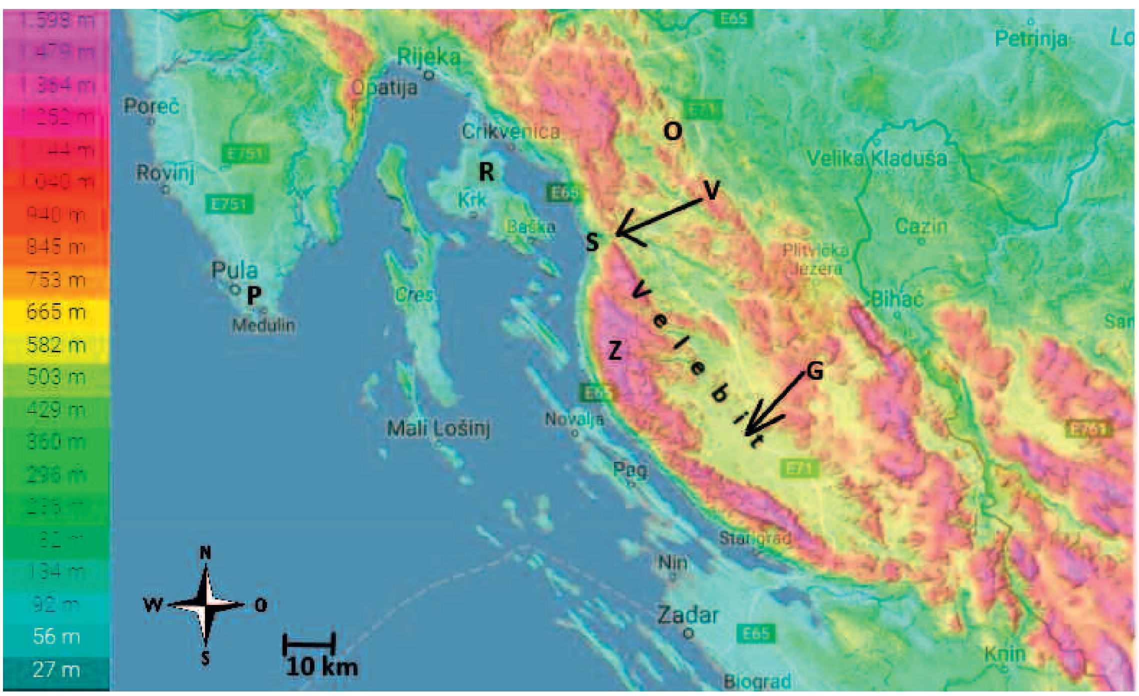


Figure 1. Map of the north-eastern Adriatic coast and its surroundings. Colors show the terrain-height. Letters indicate the station locations. P, R, O, V, S, Z and G indicate respectively Pula, Rijeka/Krk, Ogulin, Vratnik Pass, Senj, Zavižan and Gospić *(topographic-map, 2017). Modified by L. Josipović.*

Slika 1. Karta sjeveroistočne obale Jadrana i okolice. Boje pokazuju nadmorsku visinu. Položaj meteoroloških postaja je označen slovima, P (Pula), R (Rijeka/Krk), O (Ogulin), V (Vratnik), S (Senj), Z (Zavižan) te G (Gospić). *(topographic-map, 2017). Obradio L. Josipović.*

This model is applied over the Med-CORDEX domain (https://www.medcordex.eu) at a convection-permitting resolution of 0.025° (~ 3 km). A double-step one-way nesting strategy is applied. ERA-Interim drives a coarse-grid COSMO-CLM simulation (grid-distance 0.11°, 12 km) with a domain slightly larger than the official Med-CORDEX domain. In a second step, the resulting three-hourly output of this simulation drives the fine-grid 0.025° simulation. The study domain consists of a 250 x 200 $km^2$ area in the region of the Croatian part of the Adriatic.

All COSMO-CLM simulations performed in this study use the 5$^{th}$ order Runga-Kutta split-explicit time stepping scheme (Wicker and Skamarock, 2001), the land surface parametrization TERRA (Doms et al., 2011), the Ritter and Geleyn (1992) radiation scheme and a one-moment microphysical scheme (Steppeler et al., 2003). In addition, as recommended by Brisson et al. (2015), in the finest nest, the one-moment microphysical scheme predicts the mass evolution of graupel in addition to the four standard hydrometeor types (i.e., cloud droplets, raindrops, cloud ice, snow). Finally, in the finest nest, the deep-convection parameterization and subgrid-scale orography parameterization are switched off. The simulations ran from December 1999 to November 2000. This restricts our analysis period to these months. The relevant simulation data were extracted by nearest neighbour interpolation.

### 2.3. Wave breaking and gap wind events

Only the strongest events of wave breaking and gap winds were used in the analysis. These events were selected based on the following three criteria: (1) measured wind from a direction between 0° and 110° in case of wave breaking, and between 30° and 105° in case of gap winds because of the geographical position of Pula as seen from Senj, and (2) measured wind speed equal to or greater than 10 $ms^{-1}$, except for Rijeka/Krk with a threshold of only 7 $ms^{-1}$ because of lacking data, and to ensure a critical number of events. Additionally, (3) only days with a critical layer were selected as wave breaking events: the wind directions of the time step with the maximum surface wind speed are therefore investigated on the occurrence of a critical layer (i.e. a layer with phase speed of gravity waves equal to the flow speed) between the geopotential height levels of 925 and 200 hPa for each event. Indeed, wave breaking in the Dinaric Alps only occurs when such a critical layer is present (Durran, 2003).

### 2.4. Model scores

The simulations were evaluated in terms of bias scores, hit rates and false alarm ratios. For details about the calculation of these scores see Jolliffe and Stephenson (2011). For this purpose, only time steps for which observations exist were used. To compute the scores, in case of wave breaking, only the wind on Zavižan and, in case of gap winds, only the wind in Senj is considered. These observation points are chosen here, exemplarily, as their surroundings have the most complex orography of all stations. It will be determined how many times critical values (see chapter 2.3) for the appearance of both phenomena were observed and simulated.

## 3. RESULTS

After the investigation in vertical cross-sections regarding the wave breaking, section 3.1 shows averaged events and statistics. This section‘s second part deals with results in terms of the gap winds.

### 3.1. Wave breaking

Eight events were selected: on December 15$^{th}$ and 19$^{th}$ 1999 and on January 15$^{th}$ and 23$^{rd}$, April 6$^{th}$, June 7$^{th}$, July 9$^{th}$ and October 10$^{th}$ of the following year. All of them are reproduced by the fine-grid simulation. In the coarse-grid simulation, stronger wind speeds are present in the lee during an event, but the wind strength at Rijeka/Krk does not significantly differ from that in the luv of the Dinaric Alps (Ogulin, Gospić). The latter implies that the coarse simulation cannot realistically reproduce the wave breaking.

#### *3.1.1. Vertical cross sections*

On January 16$^{th}$ and October 7$^{th}$, 2000, in agreement with both simulations, a critical layer did not exist. Therefore, in those cases, the increased wind speeds at Zavižan and Rijeka/Krk cannot be explained by wave breaking, and, thus, will not be further dis-

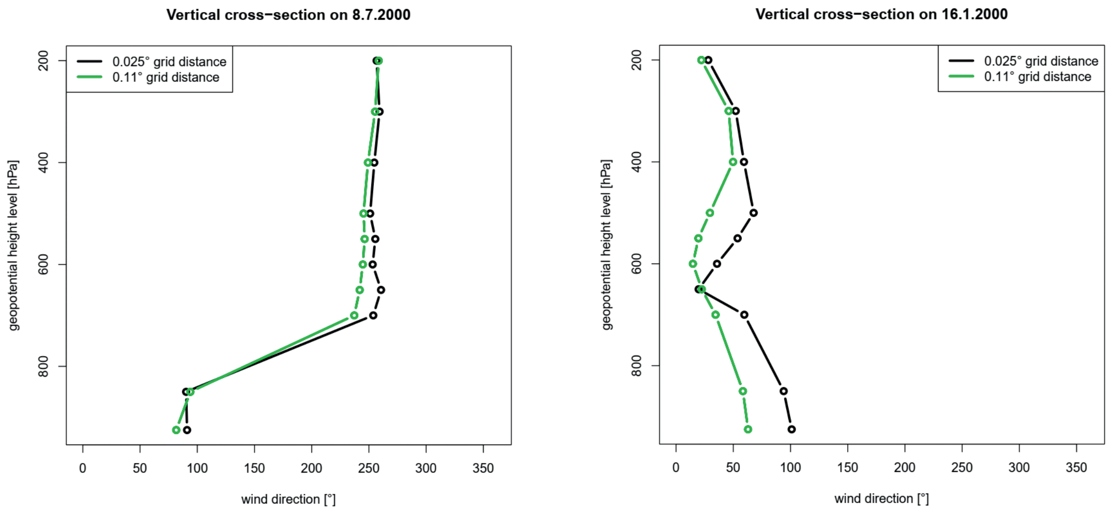


Figure 2. Bora events at station Zavižan: with a critical layer on July 8th, 2000, at 18 UTC (left) and without a critical layer on January 16th, 2000, at 21 UTC (right).

Slika 2. Bura na Zavižanu: s kritičnim slojem 8.7.2000. u 18 UTC (lijevo) i bez kritičnog sloja 16.1.2000. u 21 UTC (desno).

cussed here. This yields six events in both the fine and the coarse simulation with an existing critical layer. Figure 2 exemplarily shows a height distribution of the wind directions at station Zavižan in cases with and without a critical layer respectively. The case in Figure 2a shows a jump in the wind direction from about 90° below 850 hPa to about 250° above 700 hPa. Contrarily, the vertical cross-section in Figure 2b shows north-easterly flow in all model layers.

### *3.1.2. Average event, records and model scores*

Figure 3 illustrates the wave breaking appearances by means of an evolution of the wind speed that is averaged over six events. While differences up to 15 $ms^{-1}$ and 10 $ms^{-1}$, respectively, occur between the lee and the windward side in the observations and the fine simulation, the deviation of the values in the coarse data is partly even negative.

Six-events mean lifetime values were calculated for a better comparison of observations and simulations. As the observations are too fragmentary and the events are not visible in the coarse simulation, lifetimes were only determined from the high-resolution simulation. The average lifetime is 24 ± 4 hours on Rijeka /Krk. The longest of all investigated Bora events occurred there on January 14th 2000 and took 55 ± 1 hours, i.e. more than two days. On Zavižan, the average lifetime was 56 ± 12 hours and the longest event took 100 ± 1 hours on December 19th 1999, i.e. more than four days.

Six-events mean maximum wind speeds were calculated from all three data sources. The highest wind speeds in the observations and the coarse-resolution simulation occurred on December 12th 1999. In the high-resolution simulation, a higher value was simulated only for Zavižan on January 23rd 2000. Table 2 shows all the six-events mean and total maximum wind speeds.

While comparing Figure 3a with Figure 3b, it appears that the high-resolution simulation for Rijeka/Krk exceeds the observations, whereas for Zavižan the opposite happens. The wind speed on Rijeka/Krk increases by 10 $ms^{-1}$ at the beginning of a wave breaking event in the more precise simulation, while only 8 $ms^{-1}$ of acceleration are measured there. On Zavižan, the wind also rises by 10 $ms^{-1}$ on average in the high-resolution simulation, but a twice as high mean value is observed.

Compared to those values, Figure 3c shows only a little increase of about 5 $ms^{-1}$ for Zavižan. For Rijeka/Krk the low-resolution simulation

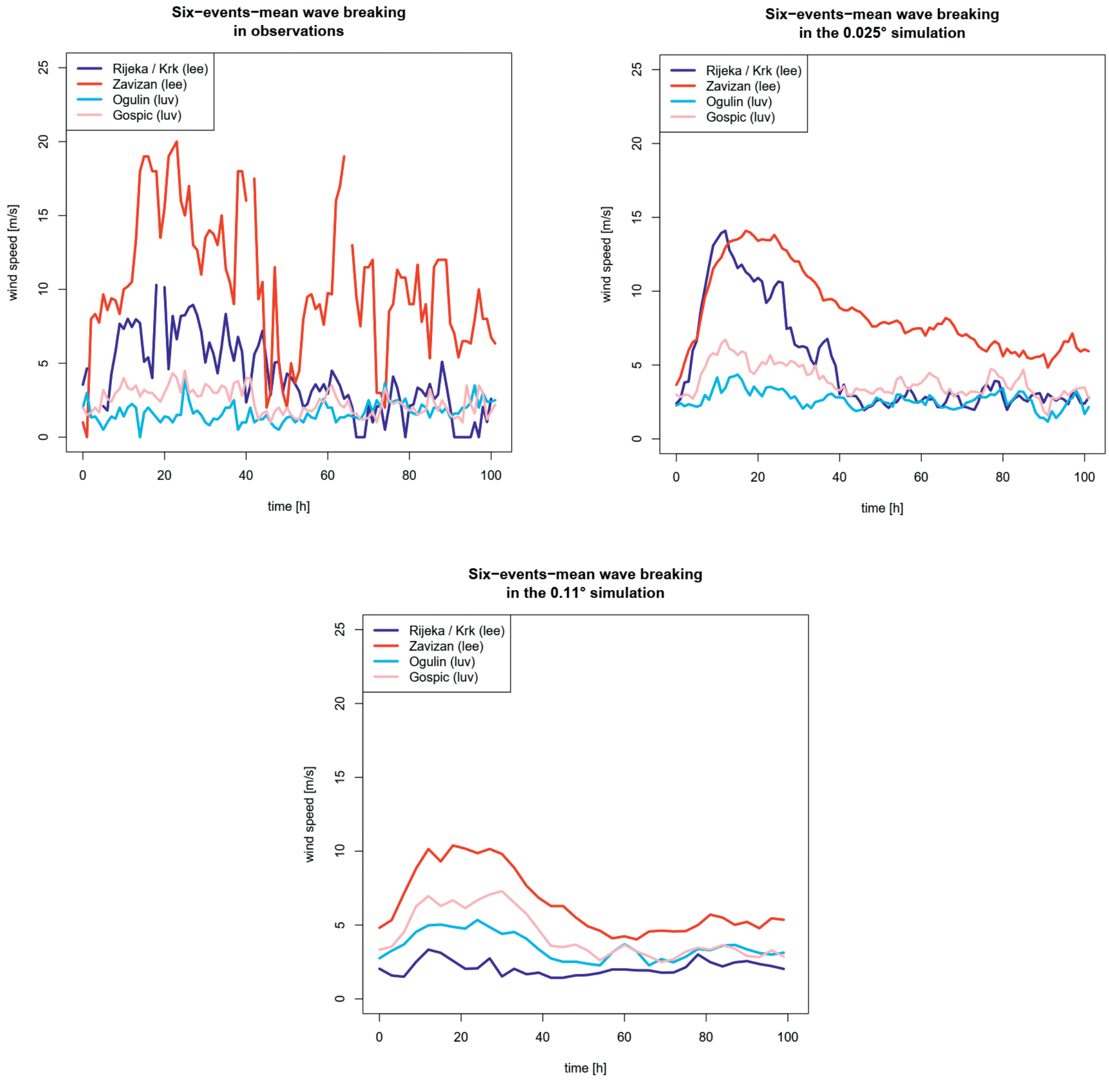


Figure 3. Six-events mean wave breaking wind speed depending on the time since the beginning of the event: a) in measuring data (left), b) the 0.025°-simulation (right) and c) the 0.11°-simulation (bottom).

Slika 3. Prosječno lomljenje gravitacijskih valova (srednjak od šest događaja): a) razvoj brzine vjetra u vremenu od početka događaja u mjerenju (lijevo), b) u 0,025°-simulaciji (desno) te c) u 0,11°-simulaciji (dolje).

Table 2. Six-events mean and total maximum wind speeds in Rijeka/Krk and on Zavižan in $ms^{-1}$.

Tablica 2. Srednje maksimalne brzine vjetra (usrednjeno za šest događaja) i apsolutne maksimalne brzine vjetra na postajama Rijeka/Krk i Zavižan u $ms^{-1}$.

| | **Six-events-mean maximum wind speed** | | **Absolute maximum wind speed** | |
|---|---|---|---|---|
| | **Rijeka (Krk)** | **Zavižan** | **Rijeka (Krk)** | **Zavižan** |
| **Observations** | 10 ± 1 | 16 ± 2 | 15 | 23 |
| **0.025° simulation** | 16 ± 2 | 15 ± 2 | 22 | 18 |
| **0.11° simulation** | 5 ± 1 | 11 ± 2 | 8 | 15 |

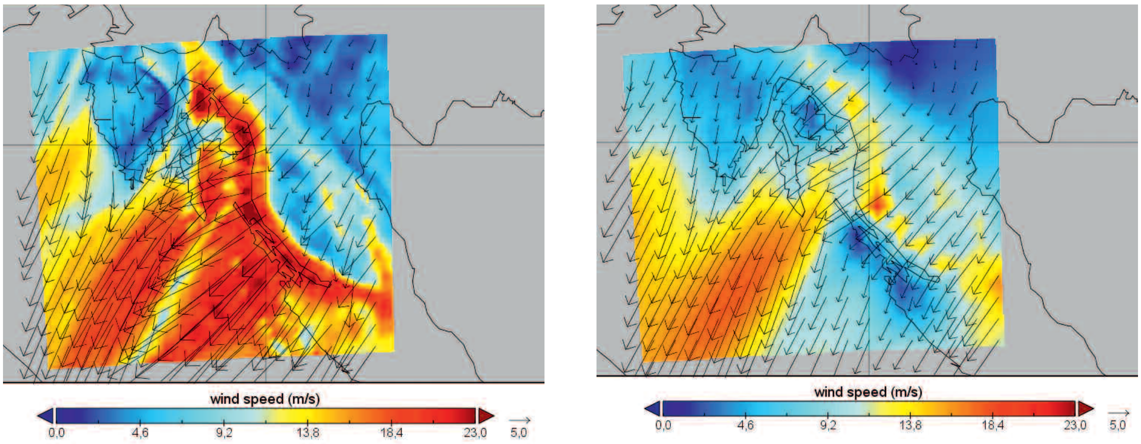


Figure 4. Simulated wind fields of the wave breaking event on December 20th 1999 at 21 UTC with: a) 0.025° (left) and b) 0.11° grid distance (right).

Slika 4. Simulirano polje vjetra kod lomljenja gravitacijskih valova, 20.12.1999. u 21 UTC, za dvije horizontalne rezolucije: a) 0,025° (lijevo) te b) 0,11° (desno).

does not even predict an acceleration of the wind speed, hence, it can be concluded that the coarse simulation cannot reproduce a wave breaking event on average. The wind speeds on Zavižan are lightly intensified though, which can be explained by the vanishing frictional effects of the boundary layer in the height of the meteorological station (about 1600 m amsl).

The greatest six-event mean maximum wind speed of Rijeka/Krk is found in the high-resolution simulation whereas the low-resolution simulation shows an average maximum wind speed of only 5 $ms^{-1}$ during wave breaking events (Tab. 2, Fig. 3). On Zavižan, the observed maximum wind speed was 16 $ms^{-1}$ on average. The high-resolution simulation predicts an almost identical value on average while the low-resolution simulation shows a mean maximum that is about one third smaller.
The absolute maximum wind speeds lead to the same conclusions: the greatest absolute wind maxima were predicted by the high-resolution simulation for Rijeka/Krk (about 22 $ms^{-1}$) and observed on Zavižan (about 23 $ms^{-1}$). The low-resolution simulation shows much weaker wind speeds for both locations.

Table 3. Model scores for both simulations on calculating wave breaking events on Zavižan.

Tablica 3. Uspješnost modela u simulaciji lomljenja gravitacijskih valova na postaji Zavižan za dvije horizontalne rezolucije.

| | **0.025° simulation** | **0.11° simulation** |
|---|---|---|
| **Bias score** | 0.83 | 0.21 |
| **Hit rate** | 0.60 | 0.21 |
| **False alarm ratio** | 0.27 | 0.16 |

Figure 4 shows how wave breaking events look like in the wind fields of both simulations on December 20th 1999.

The effect of wave breaking signed by a red colored zone of wind speeds over 15 $ms^{-1}$ that runs along the coast in the high-resolution simulation (Fig. 4a). At the same time, two gap jets are visible. In the low-resolution simulation (Fig. 4b), wave breaking can only be found as a broken, yellow area.

The model scores show that both simulations underestimate the wind speeds on Zavižan (Tab. 3). This effect is stronger in the low-resolution simulation. While the high-resolution simulation predicts 60 % of the events correctly, the low-resolution simulation simulated 21 % true.

### 3.2. Gap winds

The six selected events occurred on December 5th, 12th and 19th 1999 and on January 9th, May 13th, and August 25th of the following year. Whereas the high-resolution simulation captures them all, the low-resolution simulation missed the gap wind in May 2000.

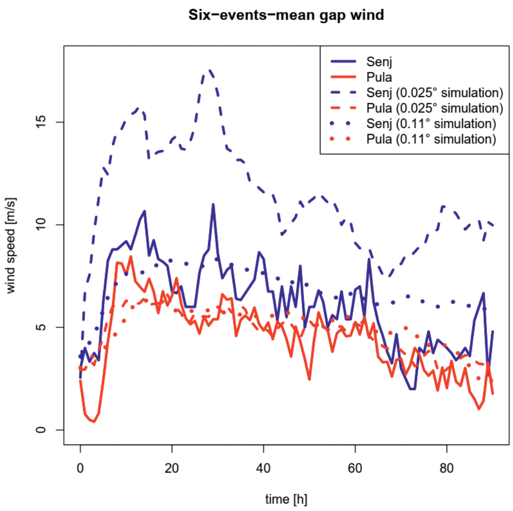


Figure 5. Six-events mean gap wind in measuring data and both simulations: wind speeds depending on the time since the beginning of the event.

Slika 5. Prosječni kanalizirani vjetar (srednjak od šest događaja) mjereni te dobiven s obje simulacije: razvoj brzine vjetra u vremenu od početka događaja.

Figure 5 shows the six-events-mean gap wind analog to Figure 3. The typical design of a gap wind can be found in each of the data sources. At first, the wind speed increases directly at the end of the gap. In Pula, at a distance of 60 km, the wind speed also rises, but with a certain delay and weaker due to frictional effects.

The high-resolution simulation overestimates the wind speeds of the gap jet at Vratnik Pass (Senj) on average. In some cases, this simulation predicts wind speeds that are over 100% greater than the observations. For Pula, the six-events mean prediction of the high-resolution simulation, in general, deviates less than 1 $ms^{-1}$ from the mean observation. In contrast to the wave breaking events, the lower resolving simulation also shows significant increases in wind speed. The gap wind with the longest duration was measured on January 9$^{th}$ 2000, in agreement with both simulations, and lasted approximately three days (Tab.4).

The maximum wind speed of the whole observed period in Senj is dated on December 20$^{th}$ 1999 in agreement with all data sources (Tab. 5). Furthermore, the meteorological station of Senj measured the same maximum value on the 5$^{th}$ of the same month and on January 10$^{th}$ and 11$^{th}$ of the following year. In Pula, observations and simulation data disagree regarding the total maximum. Whereas the station of Pula measured the maximum wind speed on December 5$^{th}$, the high-resolution simulation maximum is dated on December 16$^{th}$ and the low-resolution simulation on December 20$^{th}$ 1999.

Table 4. Six-events mean and maximum lifetimes of gap winds in hours.

Tablica 4. Srednje (za šest događaja) i maksimalno trajanje kanaliziranog vjetra u satima.

| | **Six-events-mean lifetime** | | **Maximum lifetime** | |
|---|---|---|---|---|
| | **Senj** | **Pula** | **Senj** | **Pula** |
| **Observations** | 51 ± 12 | 41 ± 8 | 87 | 68 |
| **0.025° simulation** | 49 ± 11 | 41 ± 12 | 87 | 74 |
| **0.11° simulation** | 47 ± 12 | 39 ± 11 | 77 | 71 |

Table 5. Six-events mean and total maximum wind speeds in Senj and Pula in $ms^{-1}$.

Tablica 5. Srednje maksimalne (usrednjeno za šest događaja) i apsolutne maksimalne brzine vjetra u Senju i Puli u $ms^{-1}$.

| | **Six-events-mean maximum wind speed** | | **Total maximum wind speed** | |
|---|---|---|---|---|
| | **Senj** | **Pula** | **Senj** | **Pula** |
| **Observations** | 11.5 ± 0.3 | 11 ± 2 | 12 | 16 |
| **0.025° simulation** | 19 ± 2 | 9 ± 1 | 26 | 12 |
| **0.11° simulation** | 10 ± 1 | 9 ± 1 | 13 | 12 |

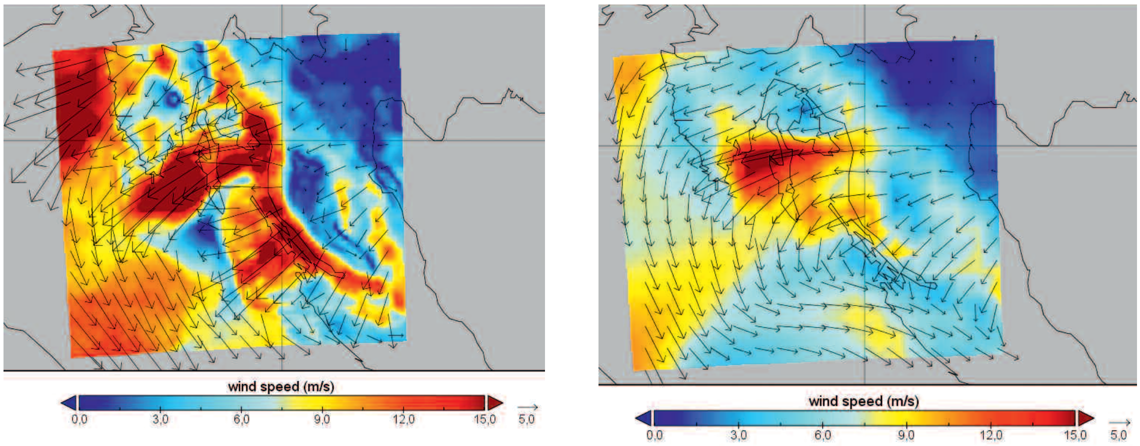


Figure 6. Simulated wind fields of the gap jet event on December 5th 1999 at 9 UTC with a grid distance of a) 0.025° (left) and b) 0.11° (right).

Slika 6. Simulirano polje kanaliziranog vjetra, 5.12.1999. u 9 UTC, za dvije horizontalne rezolucije a) 0,025° (lijevo) te b) 0,11° (desno).

The observed mean maximum of wind speed during a gap wind event (about 11 $ms^{-1}$ at both stations) is even closer to the mean prediction of the low-resolution simulation than to that of the high-resolution simulation. A similar difference occurs between the observed absolute maximum wind speed and that of the high-resolution simulation. This simulation overestimates the absolute wind maximum more than twice (26 $ms^{-1}$ simulated vs. 12 $ms^{-1}$ observed), even with the maximum's correct date (December 20th 1999). Compared to that, the absolute wind maxima at Pula are relatively close. It can be deduced that both simulations can resolve the gap jets at Vratnik Pass (Senj), although with different intensities.

Figure 6 gives an example of the look of a gap jet in the wind fields of both simulations.

In both Figures 6a and b, the gap jet appears as a red colored band of wind speeds greater than 15 $ms^{-1}$ that proceeds westward from Vratnik Pass. In the wind field of the high-resolution simulation, a second gap jet occurs in the region of Oštarijska Vrata Pass. However, the low-resolution simulation did not predict that gap jet. The presented results imply that the high-resolution simulation has a high false alarm ratio and a bias score above 1 for predicting the exceedances of the critical values for Senj. This hypothesis bases on the maximum wind at Senj during a gap wind event being calculated nearly twice as high by the 0.025° simulation than observed in mean (see Table 5). At the same time, the low-resolution simulation probably misses fewer gap winds than wave breaking events so that the corresponding bias score should be closer to the ideal value of 1.

This verifies the above assumed high false alarm ratio of the higher resolving simulation and a correspondingly high bias score of 4.79. (Tab. 6). Indeed, the bias score of the lower resolving simulation is with a value of 0.32 closer to 1 and, therefore, a bit higher as for the wave breaking events, but the hit rate is about 1 % smaller. The model scores show that the fine simulation highly overestimates the wind speeds at Senj. To the contrary, the coarse simulation misses most of the relevant events.

Table 6. Model scores for both simulations on predicting gap jets in Senj.

Tablica 6. Uspješnost modela u simulaciji kanaliziranih vjetrova na postaji Senj za dvije horizontalne rezolucije.

| | 0.025° simulation | 0.11° simulation |
|---|---|---|
| **Bias score** | 4.79 | 0.32 |
| **Hit rate** | 0.93 | 0.20 |
| **False alarm ratio** | 0.81 | 0.38 |

## 4. DISCUSSION

### 4.1. Wave breaking

The high-resolution simulation predicts a three times as high total maximum wind for Rijeka/Krk as the coarse-resolution simulation (Fig. 3, Tab. 2) although both simulations dated that maximum to December 20th 1999. On Zavižan, the discrepancy of a third between the observed value and the low-resolution simulation on the same day is remarkable. The large differences between both simulations are probably a result of the difference in grid distances. Figure 7 shows what this means to the resolution of the orography on the Adriatic.
The large differences between both simulations are probably due to the difference in grid distances. Figure 7 shows what this means to the resolution of the orography on Adriatic.

For example, Velebit Mountain (top at 1597 m amsl, Zavižan station) has a height of 1317 m in the high-resolution simulation while the low-resolution averages the terrain so strongly that the mountain top is only at 777 m (see Table 1). The gravity wave trigger (i.e. the mountain) is, therefore, underestimated. It ensures that, during the process of wave breaking, less potential energy can be turned into kinetic energy and the overflowing air masses can be accelerated less. The result is a lower wind speed within the low-resolution simulation.

The high-resolution simulation often overestimates wind speeds compared to observations on Rijeka/Krk. In the results of this study, however, no consistent explanations can be found for these overestimations. Partly, they could result from the turned off parameterization of the subgrid-scale orography during the runs of the simulations. Thus, the model supposes the orography to be smoother than it really is. Another explanation could be gap channeling that the model simulates in wrong places.

### 4.2. Gap winds

The fact that the high-resolution simulation and the observations are so close at Pula and highly differ at Senj (Fig. 5, Tab. 5) could be associated with the wind blowing only over the sea between Senj and Pula. As there is nearly no subgrid-scale orography between both cities, the effect of turning off the SSO parameterization, mentioned in chapter 4.1., interrupts at the coast and the wind speeds stop increasing. On the contrary, there is an impact that lets the wind weaken in the high-resolution simulation more strongly than observed. Maybe, the roughness of the sea surface is estimated too high in the mentioned simulation.

As the coarse simulation can resolve the jets developing at Vratnik Pass, but not the wave breaking events, their spatial extent must be big enough for both simulations to reproduce them. Because of a jet length of about 60 km in the direction of the air flow and a grid distance of 12 km, that fact seems to be plausible.

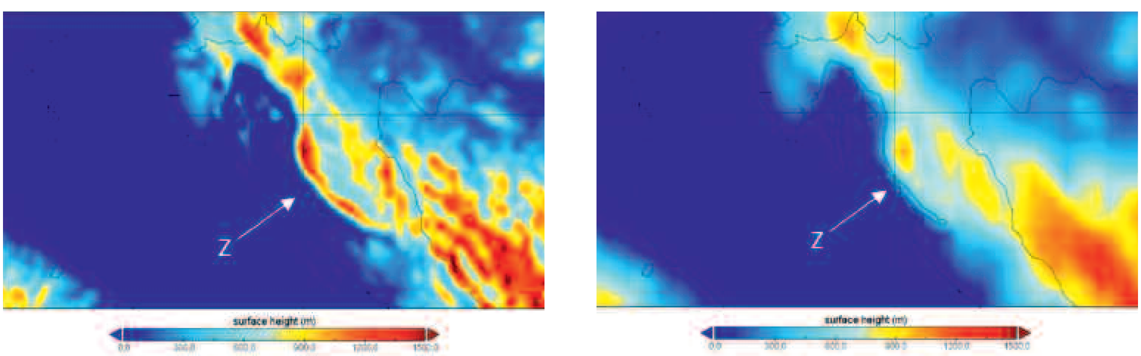


Figure 7. Orography of the Dinaric Alps on the Adriatic in the resolutions: a) of the 0.025° simulation (left) and b) the 0.11° simulation (right) with Velebit mountain in the middle of the picture. The Z indicates Zavižan station on Velebit.

Slika 7. Orografija Dinarskih Alpa uz Jadran u rezolucijama: a) 0,025° simulacije (lijevo) te b) 0,11° simulacije (desno) sa Velebitom u središtu slike. Z označava Zavižan na Velebitu.

The low-resolution simulation indeed predicts a significant increase in wind speed at the beginning of an event on average (Fig. 5). However, it does not ever exceed the 10-ms$^{-1}$-threshold. This leads to the conclusion that it would make sense to use quantiles as thresholds instead of absolute values to investigate the predictability of gap winds due to the coarse simulation.

## 5. CONCLUSION AND OUTLOOK

The question, if a convection-permitting resolution is needed to simulate Bora events realistically, is answered positively regarding wave breaking. Indeed, the fine-grid simulation better represented surface wind speeds than the coarse-grid simulation. The hypothesis that gap winds at Vratnik Pass can only be resolved by the fine simulation but not by the coarse one, is rejected. Especially, the mean and absolute maxima of wind speed during gap wind events (Tab. 5, Fig. 5, Fig. 6) show that the low-resolution simulation was partly even closer to reality than the high-resolution simulation. It is to note that the parameterization of the subgrid-scale orography was turned off for both simulations. In general, this leads to wind speed overestimation in simulations (Obermann-Hellhund and Ahrens, 2018). Hence, on one hand, the coarse-grid simulation wind speeds are higher and thus closer to the measured values as expected, as the off-turned subgrid-scale orography parameterization leads to less surface friction. On the other hand, the high-resolution simulation will overestimate the real wind speeds. Altogether, current coarse-grid RCM and GCM projections are not fine enough to be used for wave breaking investigation and thus for investigation of, for example, changes in Bora intensity with climate change. For that, finer simulations with grid distances significantly below 10 km are required.

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## SADRŽAJ
## CONTENTS