A numerical analysis of a deep Mediterranean lee cyclone: sensitivity to mesoscale potential vorticity anomalies

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Abstract:

A 12-15 November 2004 cyclone on the lee side of the Atlas Mountains and the related occurrence of severe bora along the eastern Adriatic coast were numerically analyzed using the MM5 mesoscale model. Motivated by the fact that sub-synoptic scales are more sensitive to initialization errors and dominate forecast error growth, this study is designed in order to assess the sensitivity of the mesoscale forecast to the intensity of mesoscale potential vorticity (PV) anomalies. Five sensitivity simulations are run after removing the selected anomalies, allowing for the analysis of the cyclone intensity and track, and additionally, the associated severe bora in the Adriatic. The results of the ensemble showed that the cyclone was highly sensitive to the exact details of the upper-level dynamic forcing. The spread of cyclone intensities was the greatest in the deepest phase of the cyclone lifecycle, due to different cyclone movement speeds towards the Mediterranean. However, the cyclone tracks diffluence appears to be the greatest during the cyclone movement out of the Atlas lee, most likely due to predominant upper-level steering influence and its influence on the thermal anomaly creation in the mountain lee. Furthermore, it is quantitatively shown that the southern Adriatic bora was more sensitive to cyclone presence in the Mediterranean then bora in the northern Adriatic, due to unequal influence of the cyclone on the cross-mountain pressure gradient formation. The orographically induced pressure perturbation was shown to be strongly correlated with bora in the northern and to a lesser extent in the southern Adriatic, implying the existence of additional controlling mechanisms to bora in the southern part of the basin. In addition, it is shown that the bora intensity in the southern Adriatic is highly sensitive to the precise sub-synoptic pressure distribution in the cyclone itself, indicating a close relationship between the skillful forecasting of Mediterranean cyclones and bora in the southern Adriatic

1. INTRODUCTION

The goal of this paper is to numerically analyze the sensitivity of the deep and severe impact 12-15 November 2004 Mediterranean cyclone initiated in the lee side of the Atlas Mountains to the mesoscale upper-level potential vorticity (PV) anomalies. Furthermore, the numerical analysis investigates the relationship between synoptic forcing due to cyclone presence in the Mediterranean and extreme bora along the eastern Adriatic coast.

Almost half of the cyclones that enter the Mediterranean region are North-West African (henceforth NWA) cyclones (Radinović 1987), most often initiated in the lee side of the Atlas Mountains (Pedgley, 1972, Trigo, 1999). Once they arrive over the Mediterranean Sea, these cyclones occasionally experience a strong and sometimes explosive deepening growth rates (e.g. Conte, 1985; Tripoli et al., 2005). Recently, the numerical analysis of the formation of the Nov 2004 cyclone on the lee side of the Atlas Mountains showed that this cyclone was orographically initiated in two stages in a process that resemble, but is not completely equivalent to, the Alpine lee cyclogenesis (Horvath et al., 2006).

Up until now, a number of studies on Alpine and NWA cyclogenesis (e.g. Buzzi and Tibaldi, 1978, McGinley, 1982; Pierrehumbert, 1985; Speranza et al., 1995, Pichler and Steinacker, 1987; Egger et al., 1995; Thorncroft and Flocas, 1997; Aebischer and Schär, 1998), have addressed by various methods the phases of the lee cyclone generation. These studies have confirmed that besides a mountain range induced thermal anomaly in the first phase, an upper-level trough is a necessary ingredient of the second phase of orographical cyclogenesis and then baroclinic interaction acts to deepen the two-vortex system.

Few studies have addressed the sensitivity of Alpine and NWA lee cyclones to the upper-level precursor in full-physics simulations (e.g. Zupanski and McGinley, 1989; Tsidulko and Alpert, 2001, Romero, 2007). However, by investigating the predictability of moist baroclinic waves, several recent studies showed that the small (<200 km) and medium (<2000 km) scales of motion can influence the forecast error growth (Tan et al., 2004; Zhang et al., 2007). In addition, though the apparent predictability of some cases of cyclones on the lee side of the Atlas Mountains suggested a controlling role by large-scale forcing, closer examination revealed that significant mesoscale development led to actual weather pattern (Tripoli et al., 2005). Therefore, it might be possible that a part of the predictability of the Nov 2004 cyclone on the lee side of Atlas Mountains is determined by the exact mesoscale details of the upper-level circulations, rather then large-scale features of the trough itself.

Once over the Mediterranean, deep NWA cyclones often cause strong local bora wind (in Croatian “bura”) in the southern Adriatic, which is climatologically less favorable region for bora severity. Up until now, bora has been studied primarily in the northern Adriatic (e.g. Smith, 1987, Belušić et al., 2004; Grubišić, 2004; Ivatek-Šahdan and Tudor, 2004; Göhm and Mayr, 2005), in the adiabatic framework of hydraulic and wave breaking theories. However, bora in the southern Adriatic is often associated with both upstream and downstream cloudiness and precipitation, which limits the traditional analysis in terms of e.g. Froude number, since the moist flow over the mountain ridge has considerably more degrees of freedom (e.g. Miglietta and Rotunno, 2005). A few phenomenological studies that have addressed the bora in the southern Adriatic (e.g. Jurčec, 1989; Ivančan-Picek and Tutiš, 1996) challenge the view of bora as a local small-scale phenomenon and link its multi-scale development and structure with a cyclonic activity in the Mediterranean. However, up until now, there appears to be a lack of numerical studies on the sensitivity of bora in the Adriatic to the synoptic forcing and cyclone presence in the Mediterranean which is a necessary pre-conditioning footstep in understanding the smaller-scale details of the “cyclonic” bora flows.

Motivated by the fact that the error growth is dominated by sub-synoptic scales, in this study we perform a numerical analysis of the sensitivity of the Nov 2004 cyclone on the lee side of the Atlas Mountains to the mesoscale upper-level PV anomalies through a number of arbitrary PV modifications in the initial conditions. In addition, the sensitivity of bora to the exact details of the pressure distribution inside the cyclone is evaluated from a synoptic and sub-synoptic point of view, with a special emphasis on the differences between the northern and the southern Adriatic. In section 2 we provide a synoptic overview and observational data, while section 3 describes a mesoscale model and a method used. Results of the numerical analysis are presented in section 4, and section 5 concludes the paper.

2. SYNOPTIC OVERVIEW

The synoptic setting, within which the extreme bora along the Adriatic coast developed on 14 Nov, followed an orographical cyclogenesis in the lee of the High Atlas Mountains on 12 Nov 2004 (Fig 1. and Fig 2.a-b). At low levels, a strong shear line dominated the region near the SW tip of the mountain, separating the thermal anomaly in the lee of the High Atlas from the broad-scale warm NWA and Saharan air mass (not shown, please refer to Figs 5. and 10. in Horvath et al., 2006). A strong upper-level trough reaching 12 PVU advected over the region of the Atlas Mountains and coupled with the thermal anomaly near the SW edge. A detailed analysis on the low-level conditions during the initial phase of the cyclone formation as well as satellite imagery and upper-air analysis can be found in the former numerical study (Horvath et al., 2006). Subsequently, the cyclone moved northwest towards the Mediterranean (Fig 2.c). As it was approaching the coast of southern Italy, on 13 Nov, torrential rain (overall ~250 mm/12 hr) and flash floods were recorded in Salento region, the SE part of the southern Italy, as well as heavy precipitation in the southern Croatia (123,4 mm/24 hr in village of Gornje Sito).

On 14 Nov the cyclone gradually moved towards the southern Adriatic target area. Together with a high over the Central Europe and Eastern Atlantic, this synoptic setting resulted in formation of a high-low pressure couplet conducive to the creation of high pressure gradients over Dinaric Alps (Fig. 2.d). This resulted in the onset of severe bora that caused a range of human, infrastructural and economic losses. During the episode, 10-min average wind speeds were of gale force and measured maximum wind gusts reached almost 60m/s. Besides the strength, the uniqueness of this case is characterized by 24-hr longevity and simultaneous bora existence all along the eastern Adriatic coast. Eventually, already semi-stationary cyclone slowly dissipated over the south-western Balkans.

3. DESCRIPTION OF EXPERIMENTS

3.1 Numerical model

The simulations were performed with a non-hydrostatic version of the fifth generation Pennsylvania State University - National Center for Atmospheric Research mesoscale model MM5. For this study two two-way nested domains were chosen at 21 km and 7 km horizontal resolutions with 23 vertical levels. Simulations were initialized on 00 UTC, 12 Nov 2004 and run for the 84 hours period. Initial and boundary conditions were provided by the global NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) Final Analysis (FNL). The planetary boundary layer parameterization used a version of the Blackadar scheme parameterization. Other physical parameterizations included the Betts and Miller cumulus parameterization, simple-ice explicit moisture and cloud-radiation schemes and a multi-layer soil temperature model.

3.2 Method description

The removal of the upper-level mesoscale potential vorticity anomalies from initial conditions was performed by applying the piecewise PV inversion scheme (Davis and Emanuel, 1991) on Ertel’s potential vorticity (ErPV) fields, with Charney’s non-linear balance condition. The total PV anomaly was defined as the departure from the 10-day time average (centered on 00 UTC, 12 Nov) PV field between 500 hPa and 100 hPa levels. Within the total anomaly, individual PV cores (mesoscale regions of local ErPV maximum within the trough) of interest were selected and inverted at the simulation starting time. Therefore, the perturbations are arbitrary in sense that neither their magnitude nor scale necessarily fit the initial-analysis error. After initialization (including removal of integrated mean divergence), this procedure resulted in the formation of an arbitrary six-member ensemble of initial conditions (Fig 3.a-f).

4. RESULTS

4.1 The control run

Results of the control run simulation were verified with the use of reanalysis and observation data. During the first 48hr of the simulation, mean sea level pressure and surface winds compare well in intensity with the ECMWF T511 reanalysis (~40 km resolution), while the model is erroneous in position due to the lagged cyclone movement towards the Mediterranean Sea (Fig 4.a). In subsequent period, concerning the long forecast range, pressure distribution of the cyclone and its position are forecasted satisfactory, though the cyclone intensity in the very cyclone centre (~100km) of the cyclone is somewhat overestimated (8 hPa) compared to the rather low-resolution reanalysis (Fig 4.b). However, the timing and strength of the low pressure tongue in the southern Adriatic on 12 UTC, 14 Nov important for the bora severity in the southern Adriatic (will be shown and discussed later), is well forecasted. Maximum modeled wind speeds were 31.2 ms^{-1} in the northern (Krk bridge) and 24.2 ms^{-1} in the southern (Makarska) Adriatic, while measured maximum reached 33.9 ms^{-1} and 24.4 ms^{-1} respectively. Therefore, the bora strength is of realistic accuracy, especially concerning the target forecast range (48-72hr) and the somewhat coarse 7 km grid horizontal resolution, which is not sufficient to explore the small-scale details of the bora flow. However, the authors believe this is not a drawback of the analysis, since the study, besides analysis of the Mediterranean lee cyclone, focuses on larger synoptic and sub-synoptic scale influences on bora and not its small-scale spatial and temporal variability.

4.2 Sensitivity experiments - Mediterranean lee cyclone

The initial phase of the cyclone formation is associated with moderate deepening rates, reaching no more then 5 hPa over the land of the north-west Africa, due to a mixture of both cyclogenetic and cyclolytic effects. The cyclogenetic influence primarily included orographic influence on the cyclone formation as well positive upper-level vorticity advection, while the cyclolytic weakening of the cyclone by deflection on the local orography (Horvath et al., 2006). The cyclone was the deepest in the control run, while there appears to be no cyclone deepening in the experiment with the greatest upper-level PV modification (Fig 5). This seems to be due to weaker upper-level forcing as well as low-level vortex development out of the favorable Atlas lee area (to be discussed later).

The overall strength of the jet streak is well correlated with the low pressure intensity in the baroclinic phase of no-precipitating cyclone development over the land. In accordance with the above, Horvath et al. (2006) have found that this phase of development resembled qualitative considerations of quasi-adiabatic low-level-upper-level vortex interaction (with vortices almost locked in phase) and linear instability theory. During this stage, the spread of cyclone intensities is the greatest just prior to the moment when deeper cyclones (cf. p3, p4), moving closer to the Atlas lee, impinged, deflected and weakened on the NE part of the range (18 UTC, 13 Nov). It should be noted that the cyclone was highly sensitive to the mesoscale PV perturbation that was the first to reach the Atlas range (p1). The cyclone intensity in this simulation was halved over the land, implying the high cyclone sensitivity to the mesoscale details of the upper-level precursor in the initial phase of the system formation. Upon reaching the Mediterranean Sea, the cyclones strongly deepened and moved towards the southern Adriatic area. At this stage of development, the spread of cyclone depths is the greatest in the whole lifecycle, most likely due to the different advection speeds towards the Mediterranean (see Fig 6). On 12 UTC, 14 Nov the weakest cyclone is the one with the greatest jet stream modification (p2), reaching 1002 hPa, while the rest of the ensemble members reached 982-992 hPa, with no significant spread in jet streak (or PV) intensity. Besides the p2 simulation, the cyclone depths in all simulations do not differ for more then 7 hPa at the most intense period of the lifecycle in each of the particular simulations. However, it will be shown that for the least intensive cyclone, besides the weaker influence of upper-level dynamical factors, this appears to be due not only to the slower cyclone advection towards the Mediterranean, but also different cyclone track. In addition, it should be noted that at this stage of cyclone development, cyclogenesis might be strongly enhanced by latent heat flux from the sea, which can synergistically couple with the upper-level dynamical factors, what might have reflected through a hidden synergy in our non-linear system. However, this was not within the scope of this paper and additional numerical experiments need to be done in order to assess all the factors and synergies responsible to almost explosive cyclone deepening over the sea. In the dissipation phase the cyclone intensities become more uniform, what appears to be associated with the cyclolysis in the final stage of the cyclone lifecycle.

In the initial phase of the cyclone development, the cyclone track diffluence in the ensemble of simulations shows quasi-linear propagation with time (Fig 6). The furthermost tracks (from the control run) are the ones with the greatest upper-level PV modifications (p2, p5). This appears to be due to the fact that, in accordance with conceptual models (e.g. Hoskins e al., 1985), stronger PV modifications increased the temperature of the low-level flow impinging on the Atlas Mountains more then in the other simulations, weakening the lee-induced thermal anomaly (can be inferred from Fig 9, Horvath et al., 2006). For these reasons, the low-level vortex was developing not in the very lee, but rather further to SE and away from the mountain, in the broad scale warm anomaly of Saharan origin.

As the cyclone moved towards the Mediterranean Sea, the cyclone track diffluence reached its overall maximum. In addition, at that time the cyclone tracks closer to the Atlas Mountains were deflected to the northeast near the NE tip of the range, apparently diminishing the spread of cyclone centre positions. This type of orographic influence was recently studied through identification of the control parameters (e.g. vortex Froude number) for diagnosing track deflections and. continuity for tropical cyclones traversing Taiwan (Lin et al., 2005). Though these were not tested here, it might be possible that similar control parameters exist for extra-tropical cyclones impinging on mid-latitude mountain ranges (e.g. the Appalachians, the Atlas, the Apennines).

Once cyclones reached the Mediterranean and strongly deepened, the cyclone tracks became confluent. This appears to be associated with the orography of southern Italy (Sicily and Calabria) and south western part of the Balkan peninsula, that seem to encompass a marine zone of track confluence for cyclones that move towards southern Adriatic area. In addition to the track deflection on the aforementioned mountain ranges, surface fluxes from the sea, documented to have a partial control the lee cyclone tracks over the sea (e.g. Alpert et al., 1996), might have contributed to the selection of the preferred cyclone track during the mature phase of cyclone development.

Cyclone dissipation phase was characterized with quasi-stationary cyclone positions over the Balkan peninsula in most of the ensemble members. However, in some simulations cyclones were deflected towards the northern Adriatic by the Dinaric Alps, thus increasing the spread of the cyclone centre positions. Therefore, it appears that besides steering from the upper-levels, Mediterranean mountain ranges played a crucial role in determining the cyclone track and movement throughout its lifecycle.

4.3 Sensitivity experiments – bora in the Adriatic

The sensitivity of bora to the cyclone depth intensity is investigated for the two stations in the northern and the southern Adriatic, at the locations of the Krk bridge and Makarska, respectively. Time series of mean sea level pressure in the cyclone centre and bora intensity reveal that overall, the lowest wind speeds tend to corresponded to the least intensive cyclones (Fig 7.a-b). The analysis of the maximum spread of cyclone pressures and wind intensities in the simulations reveals that the bora in the northern Adriatic was less sensitive to cyclone presence then bora in the southern Adriatic, apparently due to more pronounced cyclone contribution to the cross-mountain pressure gradient built-up in the southern part of the basin. On 12 UTC, 14 Nov the time of most intensive cyclone in the control run, the 23 hPa ensemble spread corresponded to 12 ms-1 spread in the southern Adriatic and only 6 ms-1 spread in bora strength in the northern Adriatic. Having in mind the control run and the experiment with the strongest upper-level modification and very weak cyclone still out of the target region on 12 UTC, 14 Nov (p2), it might be inferred that the cyclone presence contributed to 20% of the bora intensity at the location of the Krk bridge (n. Adriatic), and 46% in the location of Makarska station (s. Adriatic). However, it should be observed that bora intensity was not uniquely determined by the cyclone depth. In addition, it seems that the actual contribution of the cyclone to the bora in the northern Adriatic might have been even smaller, since there the overall evolution of bora appeared to be almost insensitive to the cyclone centre depth.

To further elucidate the spatial and temporal dependence of bora in the Adriatic to exact sub-synoptic pressure distribution of the cyclone as well as its sensitivity to cyclone position, we have analyzed in more detail the two chosen ensemble members. On 00 UTC, 14 Nov mean sea level pressure in the cyclone centre in reached 992 hPa the control run and 1000 hPa in p5 experiment. Comparing the two, it can be inferred that regardless of the significantly different cyclone intensities and somewhat closer position of the stronger cyclone to the target region of Dinaric Alps, maximum bora wind speed does not change notably. Thus, at the time the Adriatic Sea was still out of the influence radius of the cyclone resulting in inexistent contribution to the cross-mountain pressure gradient. In subsequent hours the cyclone experienced a NE advection and approached the Adriatic Sea. On 12 UTC, 14 Nov cyclone centers were at similar positions, reaching 984 hPa (control) and 983 hPa (p5). However, the bora strength seems to be stronger in the control run, especially in the southern Adriatic where difference in the bora intensity reached ~25% (Fig 8). This implies that the meso-β tongue of the low pressure air extending from the cyclone centre to the southern Adriatic played an important role in bora severity in the southern Adriatic area.

Finally, we investigate the relationship between cross-mountain pressure gradient and bora in the northern and the southern Adriatic (Fig 9). The pressure gradient and bora strength were highly correlated in the northern (r=0.98) and to a lesser extent in the southern Adriatic (r=0.85), where Dinaric Alps are wider and higher. Therefore, it seems that orographically induced pressure perturbations did not uniquely determine the southern Adriatic bora strength to such an extent as in the case of the northern Adriatic bora. In addition, linear regression line coefficients seem to suggest that bora in the southern part of the Adriatic basin was more sensitive to the change of pressure gradient i.e. smaller change in pressure gradient is needed for the given change in bora intensity. The above facts seem to suggest that there are some additional controlling mechanisms that determine the exact bora strength in the southern Adriatic. Furthermore, the presence of the low pressure tongue in the southern Adriatic, besides modifying the background flow impinging on the Dinaric Alps (not shown here), increased the local downstream Froude number in the lee of the mountain range through the superposition of the cyclonic and Bora (mountain induced) winds. Though it is out of the scope of this paper, we may suggest that additional analysis might reveal whether such downstream effect has a potential to account for the further propagation of the hydraulic jump, and potentially stronger offshore winds during bora events.

5. CONCLUSIONS

The sensitivity of the deep cyclone on the lee side of the Atlas Mountains (12-15 Nov 2004) to upper-level mesoscale potential vorticity anomalies has been investigated through an ensemble of numerical experiments. In addition, synoptic and sub-synoptic aspects of the associated strong bora event were analyzed with respect to the cyclone presence in the vicinity of the southern Adriatic.

The analysis showed that cyclone intensity and track are strongly sensitive to the exact details of the upper-level circulation. In the first phase of cyclone development over the land, cyclone depths correlate well with jet streak intensities that reflect the mesoscale upper-level PV modifications. However, the greatest spread of cyclone intensities was in the mature phase of cyclone development over the Mediterranean (14 Nov) apparently due to the different speeds of cyclone movement towards the sea. The greatest spread of cyclone tracks was in the region where cyclones left the Atlas Mountain area, most likely due to modified upper-level steering as well as its influence on the localization of the thermal anomaly and cyclone initiation point in the High Atlas lee. Therefore, though this ensemble study uses arbitrary modifications in the initial conditions, results seem to imply that mesoscale details of the upper-level precursor might have a potential to influence the forecast of cyclones in the lee side of the Atlas Mountains. For the analyzed case, this seems to be especially true for the cyclone position in the first phase of lee development and its intensity in the later stage of the lifecycle, which were the least accurately simulated synoptic and sub-synoptic cyclone features.

Furthermore, cyclone intensity in the Mediterranean showed strongly related with the bora intensity in the southern Adriatic, and much less with the bora in the northern Adriatic. The cyclone existence appeared to account for roughly half of the bora intensity in the southern part of the basin. In addition, it is shown that sub-synoptic details of the pressure distribution in the cyclone itself (meso-β low pressure tongue in the southern Adriatic) strongly influenced the southern Adriatic bora severity and contributed up to a 25% increase in bora intensity in the target region. Therefore, numerical prediction of the southern Adriatic bora appears to be highly dependable on the success in forecasting the exact details of a cyclone structure in the vicinity of the Adriatic region.

Furthermore, the analysis has demonstrated the strong correlation between cross-mountain pressure gradients and bora in the northern and somewhat less significant relation in the southern Adriatic. While this appears to imply that there are other controlling mechanisms that contribute to bora intensity in the southern part of the basin, further studies are needed to clarify the details and the exact mechanisms relevant to the bora in the southern Adriatic.

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Figure captions

Figure 1: The western and middle Mediterranean with sites of interest mentioned in the text. The area corresponds to an ECMWF T511 resolution model orography in the domain. The terrain contour interval is 200 m starting from 200 m, and second domain is indicated. Two dots in the Adriatic refer to the Krk bridge (north) and Makarska station (south).

Figure 2: Surface synoptic situation (ECMWF T511) showing mean sea level pressure and 10 m wind vectors at a) 11 Nov 00 UTC (prior to cyclogenesis) b) 12 Nov 00 UTC (approximate time of cyclone initiation) c) 13 Nov 00 UTC (cyclone movement towards the Mediterranean d) 14 Nov 12 UTC (the time instant of the deepest cyclone in the control run).

Figure 3: Ensemble of initial conditions at 12 Nov 00 UTC showing mean sea level pressure (solid), 300 hPa potential vorticity (shaded) and 500 hPa geopotential (dashed). Upper-left: control simulation. From upper-middle to lower-right: experiments p1, p2, p3, p4 and p5 respectively.

Figure 4: Mean sea level pressure (solid), 10 m wind vectors and the jet stream at 300 hPa (shaded) of the control run at a) 13 Nov 00 UTC and b) 14 Nov 12 UTC

Figure 5: Time-series of the mean sea level pressure values in the cyclone centers (upper row) and jet streak intensities (lower row) in the whole ensemble of simulations.

Figure 6: Cyclone tracks spread of the ensemble of simulations during the lifecycles (solid) and position of cyclone centers at 13 Nov 12 UTC (dashed).

Figure 7: Time-series of the bora wind speed (upper row) mean sea level pressure in the cyclone centers (lower row) during bora episode at the a) Krk bridge and b) Makarska station

Figure 8: Mean sea level pressure, wind vectors and wind speed of the high-resolution domain for the control run and p5 simulation. The differences in bora intensity in the southern Adriatic reach up to 25% of the intensity of the control run.

Figure 9: Cross-mountain pressure difference (taken along cross-sections shown in Fig. 8) and wind intensity of the high resolution domain during bora episode taken from all ensemble members with 3 hourly frequency in period 14 Nov 00 UTC – 15 Nov 00 UTC for a) Krk bridge and b) Makarska station. The linear regression line, regression equation and coefficient of determination are added to the figure.

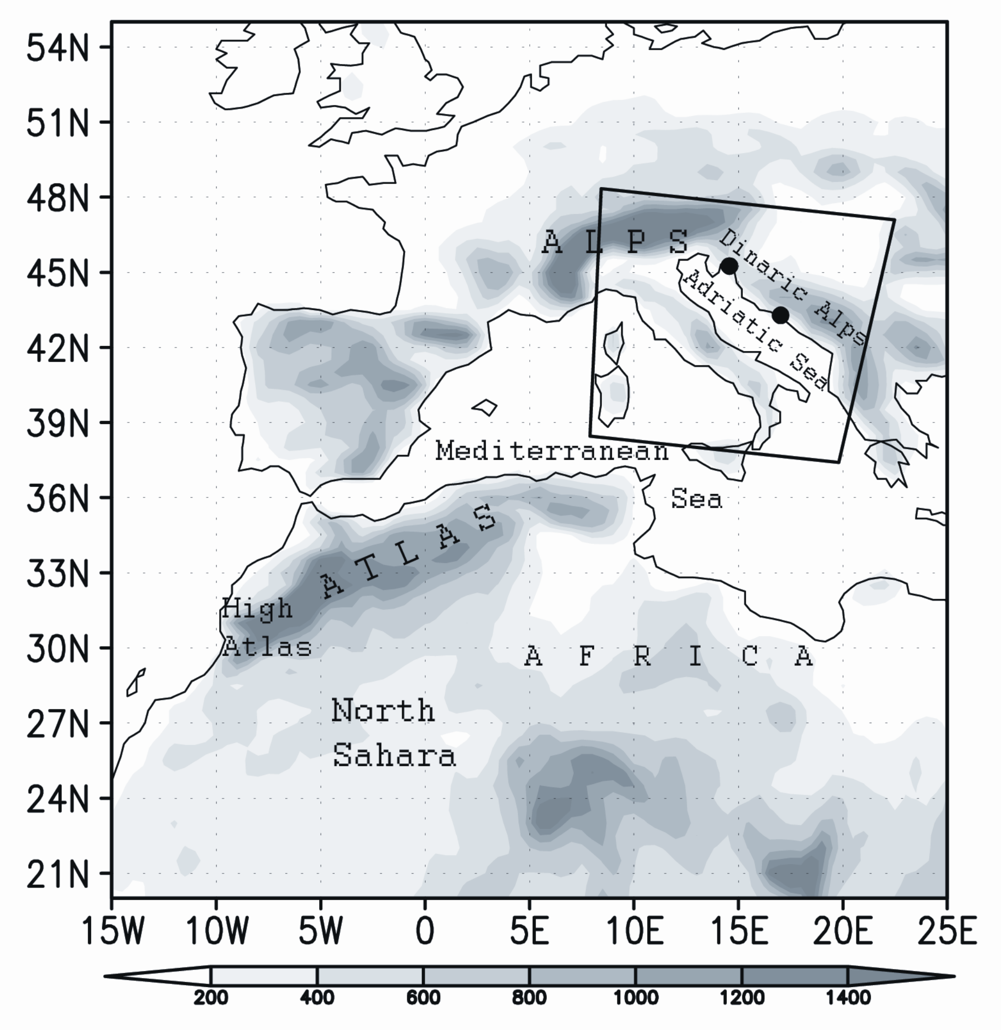


Figure 1: The western and middle Mediterranean with sites of interest mentioned in the text. The area corresponds to an ECMWF T511 resolution model orography in the domain. The terrain contour interval is 200 m starting from 200 m, and second domain is indicated. Two dots in the Adriatic refer to the Krk bridge (north) and Makarska station (south).

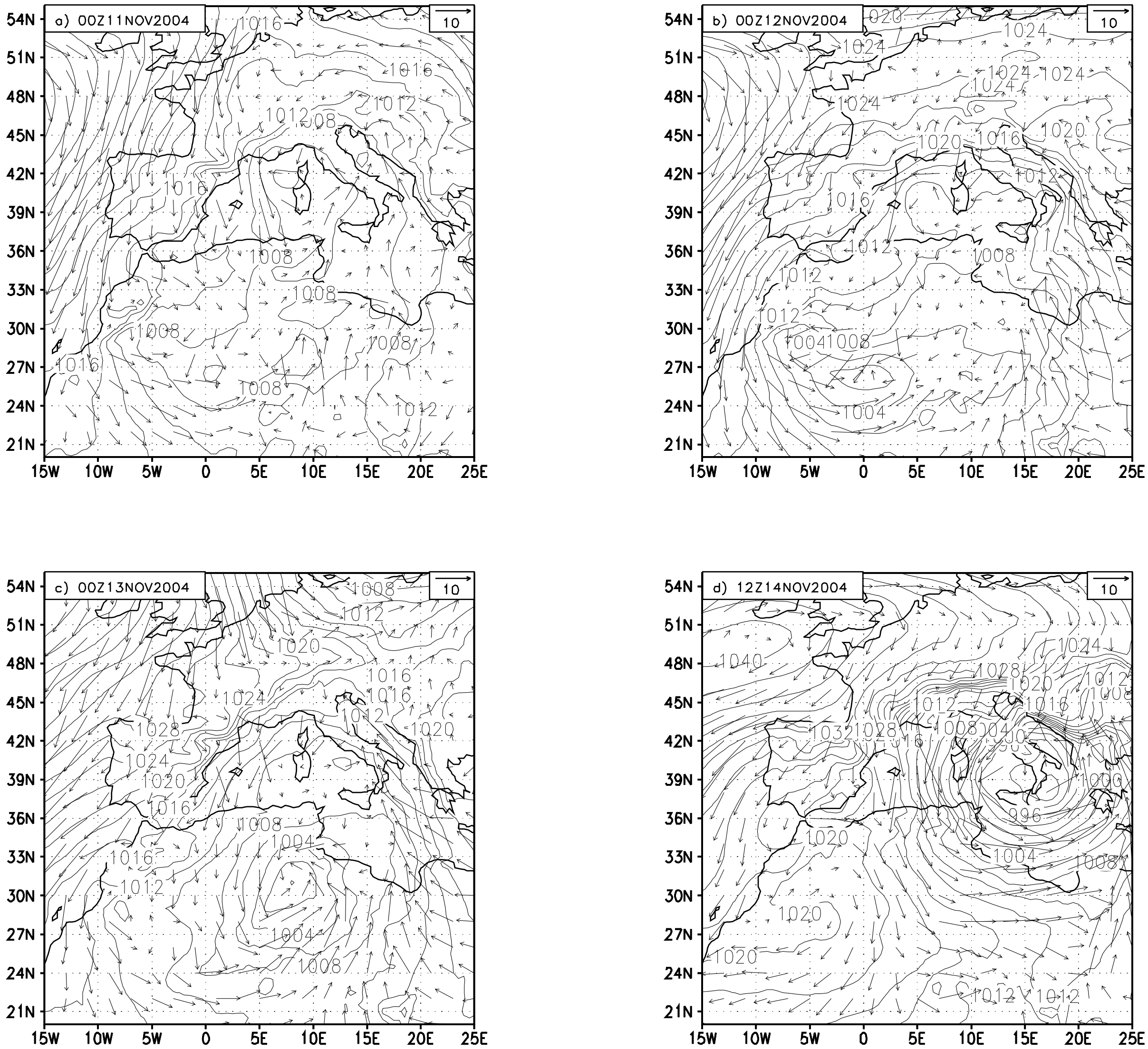


Figure 2: Surface synoptic situation (ECMWF T511) showing mean sea level pressure and 10 m wind vectors at a) 11 Nov 00 UTC (prior to cyclogenesis) b) 12 Nov 00 UTC (approximate time of cyclone initiation) c) 13 Nov 00 UTC (cyclone movement towards the Mediterranean d) 14 Nov 12 UTC (the time instant of the deepest cyclone in the control run).

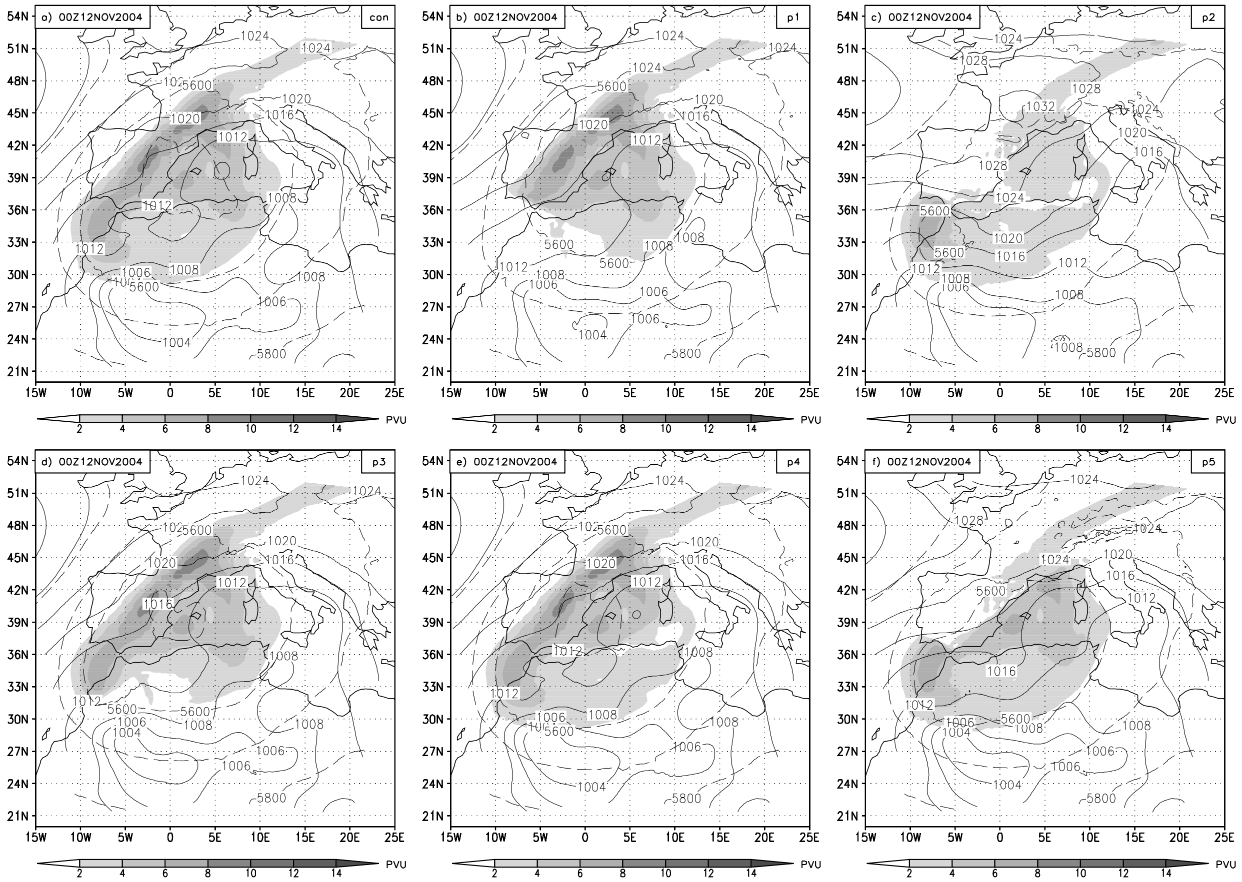


Figure 3: Ensemble of initial conditions at 12 Nov 00 UTC showing mean sea level pressure (solid), 300 hPa potential vorticity (shaded) and 500 hPa geopotential (dashed). Upper-left: control simulation. From upper-middle to lower-right: experiments p1, p2, p3, p4 and p5 respectively.

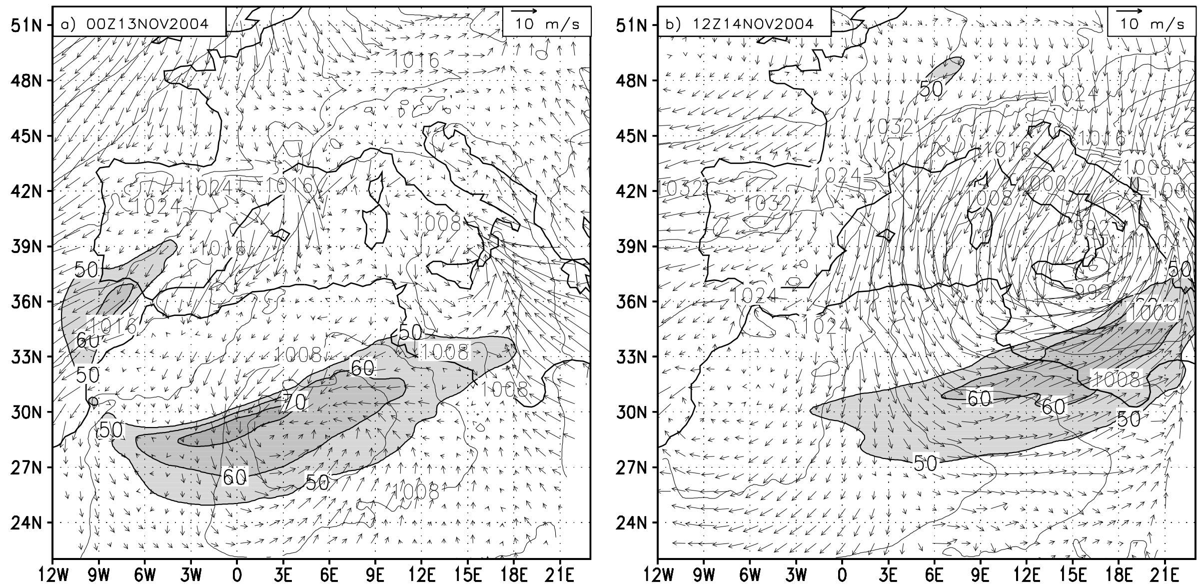


Figure 4: Mean sea level pressure (solid), 10 m wind vectors and the jet stream at 300 hPa (shaded) of the control run at a) 13 Nov 00 UTC and b) 14 Nov 12 UTC

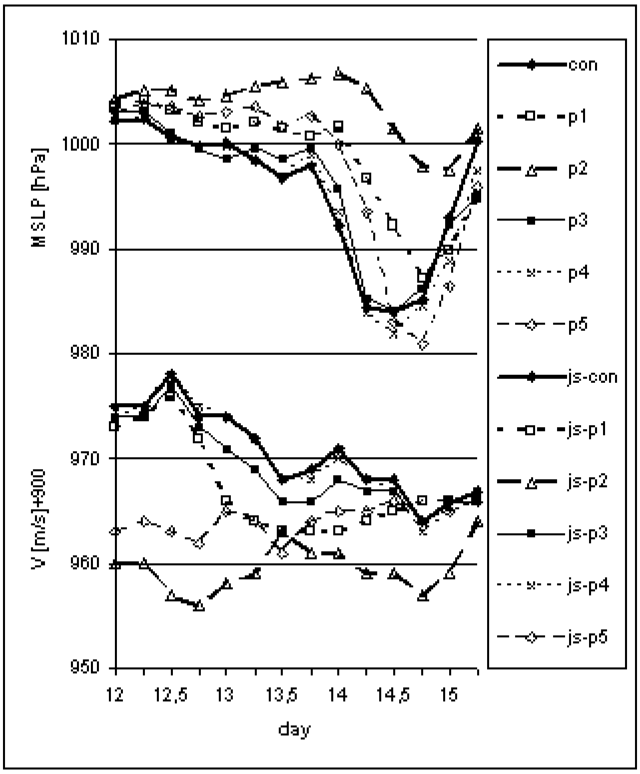


Figure 5: Time-series of the mean sea level pressure values in the cyclone centers (upper row) and jet streak intensities (lower row) in the whole ensemble of simulations.

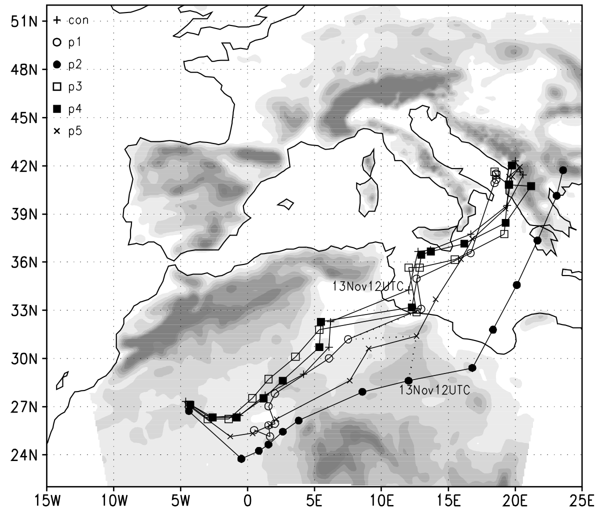
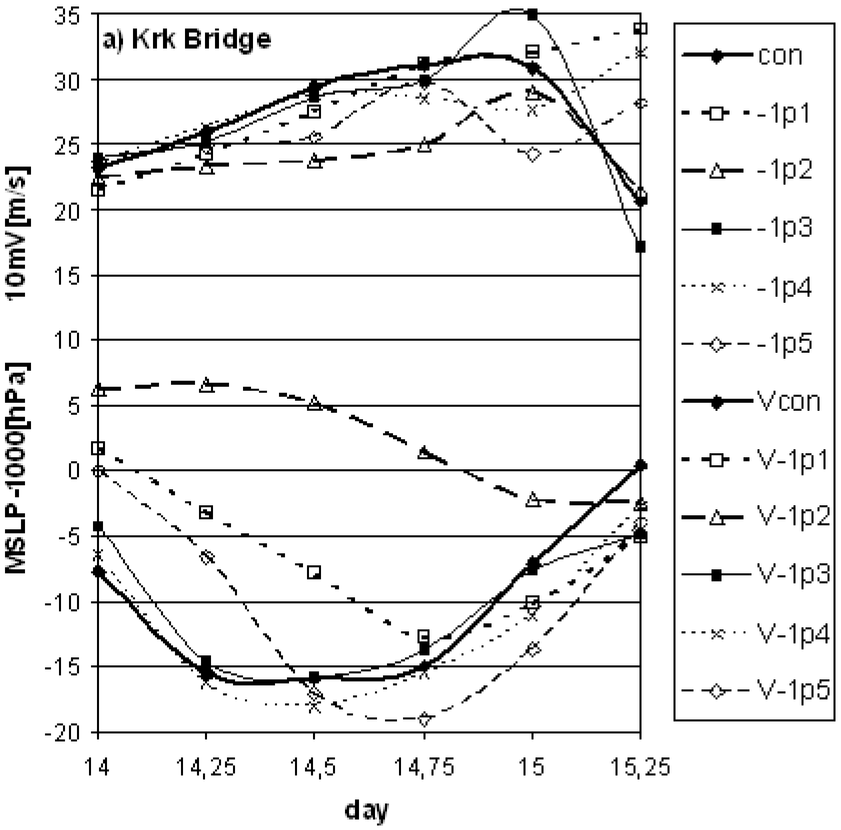


Figure 6: Cyclone tracks spread of the ensemble of simulations during the lifecycles (solid) and position of cyclone centers at 13 Nov 12 UTC (dashed).



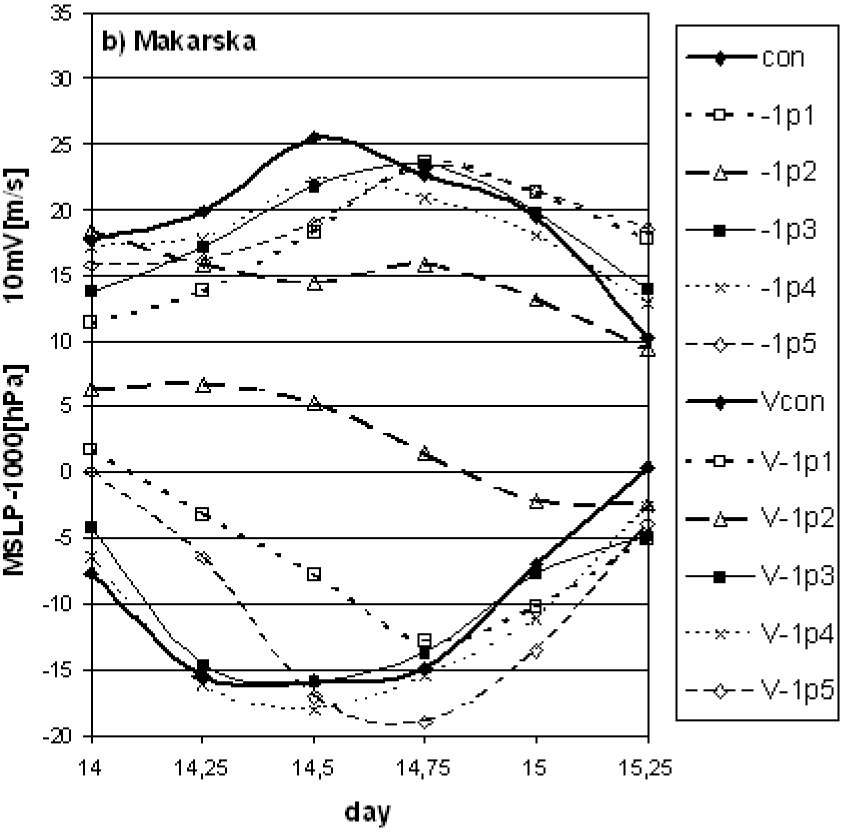


Figure 7: Time-series of the bora wind speed (upper row) mean sea level pressure in the cyclone centers (lower row) during bora episode at the a) Krk bridge and b) Makarska station

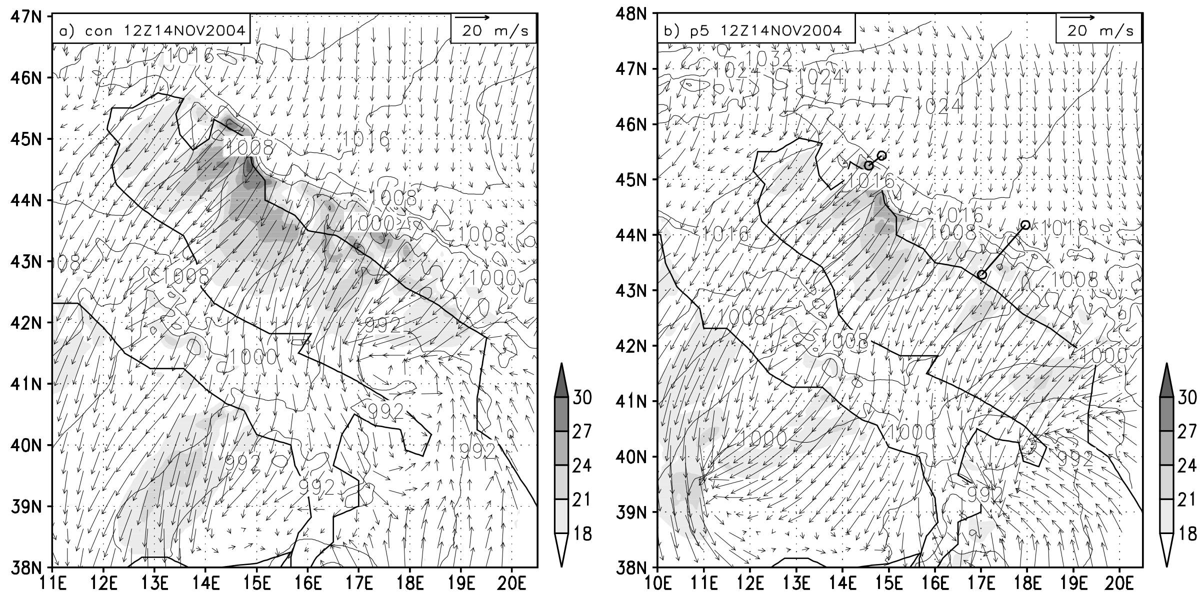


Figure 8: Mean sea level pressure, wind vectors and wind speed of the high-resolution domain for the control run and p5 simulation. The differences in bora intensity in the southern Adriatic reach up to 25% of the intensity of the control run.

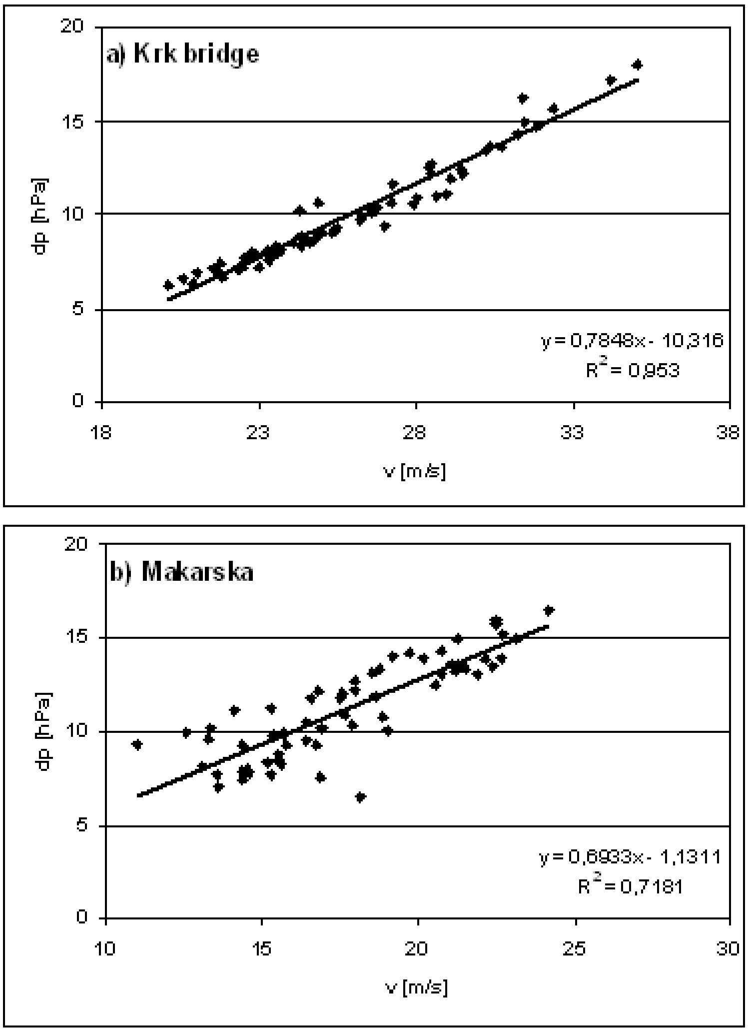


Figure 9: Cross-mountain pressure difference (taken along cross-sections shown in Fig. 8) and wind intensity of the high resolution domain during bora episode taken from all ensemble members with 3 hourly frequency in period 14 Nov 00 UTC – 15 Nov 00 UTC for a) Krk bridge and b) Makarska station. The linear regression line, regression equation and coefficient of determination are added to the figure.