Factors affecting the Adriatic cyclone and associated windstorms

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Abstract

This paper presents results of numerical experimentation of the orographic influence of the Dinaric Alps and the Apennines and of moist processes on the Adriatic cyclone and associated windstorms. The case of 28 March 1995, characterized by an intense Adriatic cyclone and damaging windstorms, is simulated using the high-resolution hydrostatic model ALADIN.

The model successfully reproduced the formation of the cyclone in the northern Adriatic and its fast movement along the basin to the south-east. The strength of associated winds, particularly severe jugo and bora along the eastern Adriatic coast, are well reproduced. Sensitivity studies confirmed that the Adriatic cyclone is an orographic lee cyclone with respect to the Dinaric Alps, although it originated as a cyclone in the lee of the Alps. The influence of the Dinaric Alps is visible in a high-low couplet over the orography due to the orographic blocking and severe winds along the coast behind the cyclone. The intensity and duration of Adriatic bora storms depend not only on a cold air supply over the Dinaric Alps but also on the lee side effects due to the mesoscale cyclone in the Adriatic sea. In addition, the appearance of the 'twin cyclone' in the Tyrrhenian sea is simulated as a realistic feature, induced by the Apennine's orography.
1 Introduction

Enclosed between the Alps to the west, the Dinaric Alps to the north and the Apennines to the south, the Adriatic region is an area where orography plays an important role in controlling weather. Severe winds, namely bora and scirocco-like wind called jugo are well known along the eastern Adriatic coast. The hourly average surface wind speed may exceed 30 m/s during the bora and jugo episodes. Bora is a gusty, downslope wind with gusts frequently reaching 45 m/s. The main local characteristics of bora appearance are its sudden occurrence and strong variations. On the contrary, jugo’s strength increases monotonously, with maxima on average smaller than those of bora. In this paper some factors influencing the appearance and intensity of bora and jugo winds will be considered. This includes two types of low levels flow, one parallel (jugo) and the other perpendicular (bora) to the Dinaric Alps. While bora appears under various upper-level flow conditions, the upper-level flow in jugo cases impinging on the Dinaric Alps is from south-westerly directions. The purpose of this study is to present the mesoscale nature of these events that results from the interaction of an intense Adriatic cyclone with the complex coastal terrain.

The ALPEX project (Kuettner, 1982) and the following theoretical research improved the knowledge about airflow over and around the mountain ranges producing lee cyclogenesis and severe downslope winds, specially the bora. The aircraft measurements over the northern part of the Dinaric Alps, together with a dense sounding network, provided the first aerial observations of the bora structure (Smith, 1987). Several 2D numerical simulations taking into account the narrow and steep orography at the northern Adriatic coast have been initialized with upstream soundings from Zagreb to study the bora-type flow (Hoinka, 1985; Klemp and Durran, 1987). The numerical simulations by Klemp and Durran (1987) showed that the essence of bora dynamics is the orographic wave-breaking related to the Froude number $\sim 1$.

In contrary to the bora, the dynamics of severe jugo in the Adriatic is poorly understood. It was translated as ‘scirocco wind’ until Poje (1992) introduced its original name into the literature, followed by Jurčec et al. (1996) who have emphasized the local characteristics of this warm, humid wind which cannot be accounted to scirocco wind systems. Strong and severe jugo is of special interest in forecasting surface winds since it induces high tides in the Adriatic, occasionally leading to a flood as far north as Venice. Palmieri et al. (1976) hinted at the influence of the Dinaric Alps during the jugo episodes. Using sensitivity options in a simple one-level model they have shown that the orography, together with surface friction, influences the surface wind direction and speed over the northern Adriatic which, in turn, causes sea level oscillations.

Synoptic and local weather characteristics during the bora and jugo episodes are discussed in several studies (e.g. Ivančan-Picek and Tutis, 1996; Jurčec et al., 1996, and reference therein). However, only little is known about the mesoscale characteristics favorable for bora and jugo intensification and their time variation. The largest problem is a lack of data for this region. Surface measurements are sparse, especially over the Adriatic, and the only operational sounding station is located north of the Dinaric Alps in Zagreb (the two other closest sounding stations are Udine in northern Italy and Brindisi on the western coast of the south-Adriatic). Therefore, the studies mentioned above mostly describe climatological characteristics or the synoptic evolution for some particular cases, and describe bora only at the coast. However, there is the evidence of strong winds at the sea surface, made visible to the ALPEX flight observers by large white caps moving away from the shore (Klemp and Durran, 1987), and to the native people by often closed ferryboat traffic during bora episodes in winter. Enger and Grisogono (1998) applied a 2D version of a model with a higher-order turbulence closure scheme to study the interaction between a state of the planetary boundary layer and bora characteristics. They show that, for the given background conditions, a thermal difference between the warmer sea surface and colder land can
lead to the offshore bora propagation over 100 km.

The problem of severe wind forecasting over the Adriatic region is closely related to the forecast of processes in the Alpine region, particularly the position and intensity of lee cyclogenesis. Numerous numerical simulations and sensitivity studies of Alpine cyclones based on the ALPEX data set (e.g. Dell'Oso and Radimović, 1984; Županski and McGinley, 1989) have emphasized the importance of adiabatic and mechanical mechanisms relative to the other physical processes. It has been noted that further improvement in the realism of simulations of the Alpine cyclones should be possible by a straightforward increase in the resolution of models used.

In his early, pioneering experiment of the Genoa bay cyclogenesis Egger (1972) has also investigated the relative (to the Alps) influence of other mountain ranges in the Mediterranean (i.e. Pyrenees and Dinaric Alps) on the cyclone development. Running a model with and without these mountains he came to the conclusion that "taking into account the Pyrenees and the Dalmatian mountains is not a necessary condition for the cyclogenesis but both mountain chains exert an influence on the development". More recently, Tafferner (1994) directed more attention to the specific topic of the Adriatic cyclone. Using a dry isentropic model with and without Alpine orography (but the Dinaric Alps kept in the model), his results reveal that the cyclone would not be generated without the presence of the Alps. However, that study did not address the question on the influence of the Dinaric Alps on the development and maintenance of the Adriatic cyclone.

There is an intimate relationship between bora, jugo and a cyclone in the Adriatic, which we wish to assess more precisely through numerical experimentation. The orography of the Mediterranean area, specially the Apennines and the Dinaric Alps surrounding the Adriatic sea channel, is favorable for the bora and jugo intensification in cases of cyclogenesis over the Po valley and the northern Adriatic with the cyclone moving southeastward along the Adriatic sea later on. Makjanić (1978) described how jugo and bora follow each other in connection with migrating cyclones: jugo prior to cyclogenesis, and bora behind the cyclone moving southeastward along the Adriatic sea. Local forecasters are familiar with the problem of early and reliable recognition of the northern Adriatic development, frequently accompanied by stormy weather. Although statistics of cyclones (e.g. Alpert et al., 1990) do not show a frequent cyclone location in the northern Adriatic it is likely that the large scale model analyses used for such studies do not resolve the Adriatic cyclone, confined in the narrow channel (about 200 km wide) between the Dinaric Alps and Apennines. On the other side, the climatological study of Adriatic cyclones using mesoscale analyses is not currently feasible due to the lack of an operational model and data scarcity. That explains an absence of references about this topic.

The current study intends to provide insight into the mesoscale characteristics of severe winds over the Adriatic region using a high resolution mesoscale model. The motivation for this work has been a participation in the international project devoted to the development of a high resolution mesoscale model ALADIN-Aire Limitée Adaptation Dynamique et Développement InterNational. The model evolving from the collaboration between Météo France and National Meteorological Services of several European countries currently joins together 13 National Meteorological Services (members of the ALADIN international team, 1997). Since July 1996 the model is running operationally twice a day for 48 hours on a domain centered over the central European region. The Meteorological and Hydrological Service of Croatia has joined the project in 1995, to overcome a lack of operational mesoscale model output which was for quite some time a major obstacle towards a better prediction and understanding of severe windstorms.

Simulations presented in this paper are carried out with a mesoscale model containing full physics on a 10 km grid, so we expect to get an insight into the mesoscale processes over the Adriatic region. In the case study selected for the present experiment we do not concentrate
on the cyclogenetic process itself, rather on the processes influencing the structure of wind and pressure fields in the lower troposphere when a cyclone has already developed.

Section 2 briefly describes a case selected for numerical experimentation, and is followed in section 3 by further numerical and modelling aspects. Results of the simulation are described and compared with some of the available observations in section 4. Sensitivity studies are used to isolate the influence of the coastal orography and of condensation processes in section 5. Finally, a general discussion and conclusions are presented in section 6.

2 Overview of the selected case

The case which occurred on 28 March 1995 is selected. This situation has been chosen as an exceptional case of cold air outbreak over the Alps that caused one of the strongest bora storms registered in the coastal region of Croatia. Strong winds blew over the entire Adriatic, SE-SW winds ahead of the cyclone, and bora starting after the frontal passage over particular locations. The event was accompanied by intense rain and snow showers, even on the outer islands along the Dalmatian coast. The maximum measured bora gusts exceeded 45 m/s, damaging the electrical power system in the coastal part of Croatia. Prior to bora, a strong to severe jugo was observed on 27 March 1995.

According to the classification proposed by Pichler and Steinacker (1987) this case belongs to the 'Überströmungs-Zyklonen' (northwesterly-type cyclones). On March 27 at 00 UTC a low of 975 hPa over northern Europe was rapidly deepening, but the upper level charts did not show a pronounced trough over the Alps, except for a relatively weak thermal trough in the direction of the western Mediterranean. In the next 24 hours both geopotential and thermal troughs deepened moving toward the Alps, and a lee cyclone developed in the northern Adriatic (Figure 1). During the morning of 28 March, a cyclone moved fast along the Adriatic sea, at 12 UTC being already in the southern Adriatic. In the rest of this paper we are mainly concentrated on the factors which dictate mesoscale and local features at lower levels during the movement of the Adriatic cyclone to the southeast on 28 March.

3 The numerical model

The numerical hydrostatic model ALADIN is designed as a limited area version of the global forecast model ARPEGE-Action de Recherche Petite Echelle Grande Echelle (Courtier et al., 1991). Therefore it keeps the same vertical discretization and physics. The main difference is the use of 2D-Fourier series instead of spherical harmonics. Following the approach of Machenhauer and Haugen (1987) Fourier series are limited by an elliptic truncation to ensure an isotropic resolution. A hybrid η coordinate (Simmons and Burridge, 1981) is used for vertical discretization. Physical parametrizations are the same for ARPEGE and ALADIN. A vertical diffusion parametrization follows Louis et al. (1982), extended by Geleyn (1987) to incorporate shallow convection at the top of the atmospheric boundary layer. A simplified Kessler-type scheme is employed for the large scale precipitation, deep convection is parametrized according to Bougeault (1983), and radiation processes according to Geleyn and Hollingsworth (1979) and Ritter and Geleyn (1992). These schemes take into account both stratiform and convective cloudiness. Vertical moisture and heat transport in the soil are parametrized in two layers. Initial and boundary conditions are obtained by interpolation from the analyses and forecasts of the global model ARPEGE to the integration domain of ALADIN. Since ARPEGE is a variable mesh model with highest resolution over the western European region the initial and boundary conditions of ALADIN have mesoscale
resolution, the ratio between the coupling and limited area model being about 3. The frequency of coupling is 6 hours and fields are linearly interpolated in between. A digital filter initialization procedure (Lynch and Huang, 1992) is applied to the initial fields after interpolation. The model integration domain consists of the inner integration zone, an outer extension zone (in order to make fields biperiodic) and an intermediate coupling zone where the large scale fields are merged with the ALADIN fields following the relaxation technique by Davies (1976). The primitive prognostic equations are solved for the wind components, temperature, specific humidity and surface pressure. The time-step algorithm (Radnoti, 1995) utilizes a three time level semi-Lagrangian scheme with a semi-implicit correction for fast gravity waves.

Since its quasi-operational start in May 1994 the model has been regularly verified against surface and upper-air observations, and current experience shows that it provides useful information for forecasting mesoscale events in the region of the Alps.

For the present study the above described version (operational at the time when the simulations have been done) of the model was used without any change except the integration domain and horizontal resolution. A domain of integration covers parts of central Europe and Balkan, the Adriatic sea and the Apennine peninsula (Figure 2). The horizontal conformal Lambert grid contains 109x111 points, with an average grid size of 10.6 km. Vertical discretization consists of 24 variably spaced γ levels, with the highest resolution in the boundary layer (5 layers inside the lowest 1 km). The pressure of the uppermost level is 10 hPa. Because of resolution and smoothing, the model orography does not reach the true crest height of the Dinaric Alps and Apennines although at this resolution it captures most of the mesoscale terrain features.

The central simulation (‘control run’) of the case is the standard simulation which takes initial and lateral boundary conditions from the operational ARPEGE results. Therefore this is a ‘pure’ forecast experiment. Besides its comparison with local measurements and objective analyses, a simulation where the model is driven by the analyses at the boundaries is carried out to assess an influence of the error introduced through the boundary conditions. To examine the effect of diabatic processes an experiment is carried out where condensation, moist convection and gridscale precipitation were switched off. Orographic influence is investigated by a common ‘no orography’ option, however in these experiments the ‘no Dinaric Alps’ and ‘no Apennines’ options were applied to see the influence of these orographies on the structure of the Adriatic cyclone and associated winds.

4 Results of the control simulation

The simulation starts at 00 UTC 27 March 1995, about 24 hours before the cyclogenesis took place which was related to a strong cold front propagating fast over the Alps. The front reached the northern Dinaric Alps at about 21 UTC, 27 March. With its passage the wind suddenly jumped from the south-west to a northerly direction, and temperature dropped between 5 to 10 °C during the next several hours. Behind the front, a northerly flow propagates toward the Dinaric Alps. Approaching the obstacle it turns to the NE direction with speed increasing. In the 12 hour-interval preceding cyclogenesis (06-18 UTC on 27 March) pressure dropped up to 17 hPa in the area extending from the Ligurian sea and the Po valley to central Europe and the Balkan peninsula (figure not shown). During this time, till 18 UTC on 27 March, the strength of jugo was increasing. Like usually in similar cases (e.g. Dell’Osso, 1984), the wind over the Mediterranean takes SW direction approaching the south-Italian coast in the Tyrrhenian sea, while the speed reduces. Entering the Adriatic, due to the channeling effects, the wind strengthens and direction becomes SE along the eastern coast. Maximal jugo speed at 18 UTC was up to 20 m/s along the
northern Adriatic coast, in agreement with synoptic observations.

A 990 hPa low, closed in northern Adriatic at 21 UTC (figure not shown), did not deepen further during the movement to the southern Adriatic. Inspection of weather maps for other cases indicates that this seems to be a common characteristics of Adriatic cyclones. A 24 hour pressure fall exceeds 20 hPa over the southern Adriatic area and the Balkan peninsula (Figure 3), the centers of the strongest pressure fall being split by the orography.

Within less than 3 hours (between 21 and 24 UTC), pressure gradients across the northern part of the Dinaric Alps and strong cyclonic circulation over the northern Adriatic have been established (Figure 4a). Another, weaker vortex in the wind field is located on the western side of the Apennines. During the next hours of integration (Figures 4b,c) both vortices move to the southern Adriatic and Tyrrenhenian sea. Upper-level charts (not presented) show a deep cyclone centered over the mid-Adriatic at 12 UTC 28 March up to 500 hPa level. On its rear side there is a NE flow over the Dinaric Alps, Adriatic sea and Apennines. The model captured exceptionally well the onset and strengthening of severe bora behind the Adriatic cyclone. After 30 hours the strongest bora behind the cyclone reached up to 25 m/s near the surface, with isotachs stretching along the coast and around the rear side of the cyclone. At this time the pressure difference across the Dinaric Alps also reached its largest value of 20 hPa (Figure 4b).

The essential feature in Figure 4b is the center of a high pressure upstream of the Dinaric Alps which develops parallel to the cyclone development. This map reveals a characteristic 'dipole structure' (Speranza et al., 1985) of the mountain induced surface pressure perturbation, well known from many numerical simulations over the Alps. At the same time such a high-low couplet over the Apennines is only noticeable in the northern part. This is in agreement with the study by Cacciamani et al. (1984) in the case study of easterly synoptic flow which developed after a cyclogenetic event during ALPEX, well-documented by data. They have found that the pressure perturbation induced by the Apennines is smaller than that induced by the Dinaric Alps while the incoming flow was substantially modified downstream of the first ridge.

The appearance of the 'dipole' as well as the motion parallel to the barrier are the distinctive features of orographic cyclones, observed in cyclones migrating on the 'warm side' of orographic ridges, irrespectively of the specific geographic location (e.g. Buzzi et al., 1987), and in any case along the nearly continuous orographic ridges that surround the northern side of the Mediterranean.

Figure 4 also illustrates how the orography acts to separate centers in the surface pressure and wind field offshore on either side of the Apennine peninsula. Mesinger and Strickler (1982) gave attention to the orographic influence on the appearance of multiple cycloonic centers in the southern Adriatic and Tyrrenhenian sea. By numerical simulations they also obtained the development of a cyclone with separated centers in the southern Adriatic and Tyrrhenian sea which they called 'eyeglasses cyclogenesis', referring to the locally used expression in Italy 'ciclogenesi ad occhiali'. Therefore, the near-surface vortex in the Tyrrhenian sea (Figure 4c) appears to be a realistic feature, well reproduced by the present high-resolution model. Such a characteristic picture can be noticed also in some other mesoscale simulations over this area although without explicit reference to the appearance of 'eyeglasses' (e.g. Pacagnella et al., 1992). In our study the name 'twin cyclones' is used instead. Further support to the realism of the obtained feature is provided in Figure 5 which shows an objective ARPEGE analysis of the mean sea level pressure over the same area at 12 UTC, 28 March. This figure reveals even stronger pressure gradients over the Dinaric Alps (the maximal pressure difference is 3 hPa larger as compared to Figure 4c).

The presence of a secondary low in the Tyrrhenian sea can be considered as a sort of secondary lee cyclone due to the presence of two nearly parallel ridges. However, in this case the Dinaric Alps act more effectively as a continuous barrier than the Apennines, so the main lee cyclone is
the Adriatic one, as will be shown later by the 'no orography experiments'. By the end of the integration, the low in the Tyrrenian sea has disappeared and the Adriatic cyclone has moved to the Balkan peninsula.

Due to the lack of surface observations over the sea the pressure and wind in the center of cyclone cannot be really verified. The climatological station Palagruža (location marked in Figure 2) provides at the moment the only surface data from the open Adriatic. While pressure record for this case is not available, available values of wind and temperature fit very well to the model values (not presented). More detailed verification is possible against the surface data closer to the coast. Mean hourly values of the mean sea level pressure, temperature and wind as measured at the mid-Adriatic coastal station Split (see location in Figure 2) are presented in Figure 6 in comparison with the model output every 3 hours at the closest grid point. Values and temporal changes of the all parameters are well reproduced by the model. The wind shift and strengthening after 30 hours of integration are correct. However, the model trends during the bora maximum (30-40 hours) are not very correct. The model could not capture the two separated maxima (one following the frontal passage and the other following the passage of the upper-level trough). The same is true for the bora weakening period (42-48 hours), when the speed is larger than observed, and pressure increases slower. The temperature fall is underestimated, probably due to the difference of 200 m between the model and real height of the station. The same kind of comparison at other coastal stations proves a good model performance in this case. It is often a problem in the operational forecast practice to provide a reliable forecast of the bora onset, which is usually very abrupt. Therefore, successful simulation in the experiment with forecast boundary conditions is very important and supports the model application for the operational use.

The orographic influence on the separation of the cyclonic centers in the Adriatic and the Tyrrenian sea is apparent in the model geopotential and temperature fields up to the 700 hPa level. An orographic deformation in the temperature field is demonstrating the position of the frontal zone in the 30 hour forecast of potential temperature at 700 hPa (Figure 7). Temperature gradients are strongest across the Dinaric Alps and over the Adriatic, on the rear side of cyclone. The maximum difference across the central part of the Dinaric Alps reaches 15 K, over the distance less than 200 km. At this same time largest isalobaric values (Figure 3) and pressure gradients (Figure 4b), followed by the maximum of bora speed (Figure 6a) are found. A real data comparison, not possible in this case, is provided by Steinacker (1981) whose analysis of the time history of a cold frontal deformation shows how such a front slows down over the Dinaric Alps in association with a cold outbreak behind it. Also in our case, a cold air outbreak seems to propagate faster on the eastern side of the Dinaric Alps.

During the jugo part of the episode (the first 18 hours of integration) the lower troposphere over the Adriatic is getting warmer and the Dinaric Alps are covered by clouds. Jugo is a flow confined to the surface. Above it, within 1 km height, only weak SW winds blow over the whole domain. Above this height the speed increases above the Dinaric Alps, Italian and Balkan peninsula, while the speed over the sea remains low throughout the lower troposphere (not shown). The vertical wind structure of the bora flow some hours later is just opposite. The wind strongly increases with height, and already at 925 hPa level (about 60 m above the sea level) the wind speeds maximum along the steep northern Adriatic coast reaches 40 m/s (Figure 8a). Isotachs of the strongest bora stretch along the coast and over the entire Adriatic as the cyclone moves along the channel. The bora flow reaches the Italian coast of the Adriatic with speed about 20 m/s. At 12 UTC, 28 March maximum wind is located in the mid Adriatic, behind the cyclone reaching 25 m/s (Figure 8b). Approaching the Italian coast of the Adriatic, wind turns cyclonically to NW direction. There are strong winds also in the Tyrrenian sea on the rear side of the 'twin' cyclone. During the morning
of 28 March there is still a strong flow around the eastern Alps acting as a 'feeder flow' to the bora. While this cold air supply weakens, the cyclone is moving faster to the south-east and the bora weakens. During the last 6 hours of integration (42-48), the bora maximum is weak, located at the mid-Adriatic coast and over the southern Adriatic.

The maximum of the bora speed is found close to the crest heights of the orography and along its southern slopes, as revealed in the previous 2D simulations. Vertical cross section across the Dinaric Alps, shown in Figure 9, shows that the wind speed above the surface reaches 24 m/s like close to the top of the mountain, as seen already at the horizontal surfaces in Figure 8. Above 2 km height the speed decreases, and above 4 km a SW flow is found. Unfortunately, the vertical structure of this severe bora obtained from the model cannot be verified because no upper air observations are available over the Adriatic. Nevertheless, verification of soundings from Udine and Zagreb with profiles extracted from the model at the same locations (figures not shown), as well as verification of surface data, shows not only that the model well captures the onset and development of the process at these locations, but also partially justifies the model results over the Adriatic region.

When applying analyses for the model boundaries one avoids introducing errors of the larger scale model forecast through the lateral boundaries, unavoidable in the operational work. This simulations shows no significant difference between experiments with forecast and analyzed boundary conditions during the first 36 hours of integration. Later on the Adriatic cyclone is 2 hPa shallower, and by the end of the simulation moves somewhat faster out of the model domain than in the 'pure' forecast experiment. Except over the southern Adriatic, results appear to be almost unaltered. So this simulation confirms the results of the previous one as well as the operational forecast of the global ARPEGE model.

5 Sensitivity tests

Three sensitivity tests are carried out to isolate the influence of the Dinaric Alps ('no Dinaric Alps' experiment), of the Apennines ('no Apennines' experiment), and the influence of condensation ('dry' experiment). They were carried out mainly to support the findings of the control simulation. The initial and boundary conditions for the sensitivity runs are provided by objective analyses. The integrations start at the same time as in the control simulation and lasts 48 hours, until 00 UTC, 29 March 1995.

5.1 No Dinaric Alps experiment

In our experiment we do not study the influence of Alps on cyclogenesis, but we wish to assess the effects of the Dinaric Alps on the cyclone maintenance. Therefore the orography along the eastern Adriatic coast is set to 10 m height. During the first 18 hours of integration, there is no significant difference between the control and the 'no Dinaric Alps' experiment, except that the fields are smoothed over the removed orography. Without the channeling effect along the eastern Adriatic coast, SE jugo wind is replaced by SW flow penetrating deeper into the Balkan peninsula over the southern Adriatic. A cyclone has formed in the northern Adriatic at the same time and of the same depth as in the control experiment. A drastic difference between the two simulations occurs after 24 hours. Without the presence of the Dinaric Alps, the low pressure field spreads over the Adriatic and the Balkan peninsula with its center moving quickly to the east and weakening. After the next 12 hours, at 12 UTC 28 March, no cyclone is present in the Adriatic (Figure 10). The northerly winds cover the entire southern Adriatic instead of NW to SW flow as predicted in the run with the Dinaric Alps (Figure 4c). The winds at the surface and throughout the lower
troposphere are generally weaker than in the control experiment. The surface wind speed along
the coast varies between 5 and 10 m/s, more than twice as weak as in the control experiment.
Offshore, over the Adriatic, wind is twice stronger than at the coast. Maximum speed near the
sea surface is around 20 m/s at 6 UTC, 28 March. The largest increase of wind speed exists near
the coast, induced by the frictional contrasts between land and sea and due to thermal differences.
The average difference of surface temperature between the Adriatic and surrounding orography,
for instance, exceeds 10 K in winter, which was the maximum temperature difference investigated
by Enger and Grisogono (1998) in their idealized simulations.

The absence of blocking upstream of the Dinaric Alps also influences the 'twin cyclone' in the
Tyrrenian sea. Northerly winds accelerating over the Adriatic cause stronger blocking effect and
a dipole structure across the Apennines. The Tyrrenian low has the same depth (i.e. 1 hPa less)
as in the control experiment, but the pressure gradients on its rear side are stronger and the center
of high pressure is shifted southeastward (to compare with Figure 4c).

There is no orographic deformation in temperature field across the Dinaric Alps, seen in the
control run (Figure 11, to be compared with Figure 7). The temperature difference between the
control and 'no Dinaric Alps' run in the mid Adriatic is up to 10 K, while upstream of the missing
orography the difference is negligible. The absence of the Dinaric Alps leads to the much faster
propagation of a cold air to the east, so the temperature gradients across the eastern Alps also
weaken faster.

Comparison between Figure 12 and Figure 8b illustrates the influence of Dinaric Alps on the
wind field in the Adriatic: the bora maximum along the coast is not present; in place of the cyclonic
circulation a strong cyclonic wind shift is found further in the southern Adriatic. Similar features
are found at other levels in the lower troposphere, with differences decreasing vertically, and no
difference at 300 hPa. At this time (12 UTC, 28 March) wind speed above the northern Adriatic
has weakened but over the (former) Dinaric Alps speed is still up to 20 m/s. In the Tyrrenian
sea the wind speed is somewhat larger and gradients stronger in comparison with the control run.

The difference between the control and the no-Dinarics run of mean sea level pressures after
36 hours is shown in Figure 13a. There is a significant difference of 14 hPa in the center of the
Adriatic cyclone. At the same location the difference in geopotential heights at 850 hPa is 80 gpm
(Figure 13b) and 47 gpm at 700 hPa (not shown). This shows that significant perturbations are
induced by the Dinaric mountain range in the lower troposphere. Strongest differences are along
the southern Adriatic coast and Dalmatian inland. In the northern Adriatic differences are small
although severe bora at this time still blew there. These results hint at some important differences
between the southern and northern Adriatic bora. The cyclone in the northern Adriatic was not
induced by the orography of Dinaric Alps. The related bora flow reached the northern Adriatic
behind the cyclone and lasted as long as northern flow was supplied around the eastern Alps. Later
on, the cyclone in the southern Adriatic contributed to the maintenance and intensity of the wind
in the southern Adriatic inducing stronger wind on its rear side. This is in agreement with a recent
study by Jurčec and Visković (1994) which has pointed out the presence of a mesoscale cyclone in
the southern Adriatic sea during 15 selected cases with severe bora in Dalmatia.

5.2 No Apennines experiment

In this experiment the orography of the Apennine peninsula starting from the Po valley is set to
10 m height. The experiment setup is like in the 'no Dinaric Alps' simulation. During the first
18 hours of simulation SW upper-level winds originating from the western Mediterranean blew
over central Italy and the Tyrrenhenian sea almost twice stronger than in the control run, while SE
jugo wind along the eastern Adriatic coast is weaker. Like previously, cyclogenesis occurred in the
northern Adriatic, but cyclonic circulation occupies much larger area than previously including northern Adriatic, central Italy and the Ligurian sea (figure not shown). However, the cyclone has the same vertical depth like previously, a maximal difference between control and 'no Apennines' simulation being 3 gpm at 850 hPa level during the whole simulation time.

The single cyclone instead of the previous 'twins' structure moved along the sea. At 12 UTC, 28 March the center of cyclone was located near the Italian coast and 2 hPa deeper than in the control run (Figure 14). Wind on its rear side is substantially stronger and the cyclonic circulation occupies a larger area of southern Italy. At the place of the former 'Tyrhenian twin' pressure is about 6 hPa higher. This figure shows that the upstream bora flow as well as the intensity of dipole structure across the Dinaric Alps are not affected by the absence of Apennines's orography. Its effects are apparent in the wind field over the Adriatic in the neighborhood of the Adriatic cyclone. Bounded to the one orographic barrier only, the cyclone has a more uniform shape and is shifted to the south. This suggests that in a case of a cold outbreak over the eastern portion of the Alps the orography of Italian peninsula influences horizontal dimensions and a location of a minimum pressure of cyclone in the Adriatic but not its vertical depth neither its movement to the south-east. Results of this experiment also confirm the role played by the Apennines on the development and maintenance of the 'twin' cyclone south of that orography.

In addition, the upstream effect of Apennines is felt in the position and strength of the bora maximum. This effect becomes visible after 6 UTC, 28 March when the cyclone moved to the southern Adriatic. Maximum of wind speed is higher as compared to the control run at the same time and it is located more to the north. This is illustrated by the wind field at 925 hPa (Figure 15). Propagation of the bora flow offshore over the Adriatic is much stronger, enters deeply into central Italy. The maximum wind at this time on the rear side of the cyclone is 9 m/s stronger. The northerly flow in the Tyrhenian sea is twice as weak as compared to the control run at 12 UTC, on 28 March (Figure 15, to compare with Figure 8b), but the wind over the southern Italy blows much stronger. This shows that a blocking due to the Apennines prevents a cold bora flow which crosses the Adriatic sea of influencing weather in Italy in the greater extent.

5.3 Dry experiment

A dry simulation, without condensation and convection, has been run to show the effects of latent heat release on the winds accompanying the evolution of the Adriatic cyclone. Prior to the cyclogenesis, there was no significant difference between the moist and the dry simulation. Some difference is found close to the sea surface along the eastern Adriatic coast, where jugo is weaker. Important difference between the dry and the moist simulation occurred after 18 UTC, 27 March related to the arrival of the cold front over the eastern Alps. In the dry simulation frontal processes are substantially weaker and the bora onset is delayed. Surface pressure gradients across the northern part of the Dinaric Alps established about 3 hours later as compared to the control run. The frontal zone above the surface was delayed even more. The strong gradients in the temperature field, in the control run well established already at 24 UTC, 27 March (presented in Figure 7 for 6 UTC, 28 March), developed only about 6 hours later, at 6 UTC, 28 March, after the NE flow was impinging on the Dinaric Alps for some hours. This shows again that the formation of a strong temperature gradient across the Dinaric Alps, which was not present in the 'no Dinaric Alps' experiment, is a deformation associated with the orographic cyclone in the Adriatic sea.

In the initial stage of development the cyclone had the same depth like in the control run while during the later development it was 2-4 hPa shallower and by the end of integration even more (figures not shown). However, its movement along the sea also in the dry simulation proves that the Adriatic cyclone is an orographic lee cyclone with respect to the Dinaric Alps.
Cyclonic circulation is substantially reduced without the effects of moist processes and bora maxima- 
ms along the coast smaller as compared to the control run. The wind strength at 925 hPa (figure not presented) is along the coast about 10% weaker than in the control simulation but the difference increases offshore and near the center of the cyclonic circulation. Cyclonic wind shift from NE to NW direction close to the Italian coast is missing. At levels above the difference is larger. Differences are most pronounced in the upper part of the cyclonic vortex, around 700 hPa as seen in Figure 16. Winds at this level are significantly weaker than in the control experiment, specially cyclonic winds over the sea. These results demonstrate the importance of moist dynamics for maintenance of the Adriatic cyclone although this influence is much less important than that of the orography. This is in agreement with other studies of Alpine lee cyclogenesis (e.g. Dell’Osso and Radinović, 1984). A remarkable influence of the moist processes in the Adriatic is found also in the fact that the surface bora strength at the coast is reduced and it spreads southwards slowly.

6 Conclusions

The overview of recent research of Adriatic storms has shown that 3D, real data numerical studies are not available. Particularly the development of an Adriatic cyclone is a mesoscale process not well understood due to the lack of data and numerical experimentations. In this study processes influencing the development and intensity of the Adriatic cyclone and associated winds are investigated. The case from 28 March 1995, characterized by damaging bora storms along the Adriatic coast of Croatia, has been simulated by the hydrostatic mesoscale model ALADIN, developed recently in the frame of international cooperation.

The presented results reveal that the ALADIN model with a horizontal resolution of 10 km is capable of giving a detailed description of the evolution of processes over the Adriatic area. The model successfully reproduced the formation of a cyclone in the northern Adriatic and its fast movement along the basin to the south-east. The strength of associated winds, particularly severe jugo and bora along the eastern Adriatic coast, are well reproduced.

Both bora and jugo winds owe their persistence to the cold (warm) air supply around the eastern Alps (from the western Mediterranean). It was shown that direction and intensity of these winds are strongly influenced by channeling effect of the Dinaric Alps. Particularly, the intensity of bora flow in the Adriatic depends not only on a cold air supply over the Dinaric Alps, but also on the downstream processes, as demonstrated by sensitivity studies. They have shown that the intensity and duration of Adriatic bora storms are affected by the moist processes inside the Adriatic cyclone and by the upstream influence of the Apennines.

The results of the simulations hint at the decisive role played by the Dinaric Alps on the maintenance of the Adriatic cyclone. The orographic influence is visible in a high-low couplet over the Dinaric Alps and severe winds along the coast behind the cyclone. Sensitivity studies confirm that the Adriatic cyclone is an orographic lee cyclone with respect to the Dinaric Alps, although it originated as a cyclone in the lee of the Alps. This behaviour depends of course on the large scale flow that favours the movement of the upper wave from NW to SE, in association with a baroclinic belt mainly along the same direction, with the temperature gradient being mainly perpendicular to the Dinaric Alps.

This study has shown that the process of Alpine lee cyclogenesis may lead to the formation of 'twin cyclones', one in the Ligurian sea and the other in the northern Adriatic. Both cyclones move southeasterly to the Tyrrenian sea and the southern Adriatic. In this case the Adriatic cyclone is the main lee cyclone whereas the 'twin cyclone' in the Tyrrenian sea developed due to the orography of Italian peninsula, as shown by the experiment where the Apennines were removed.
from the model. This also indicates the possibility of a misinterpretation of the Genoa cyclone movement to the southern Adriatic region based on synoptic time and space scales alone.

This numerical modelling study has supplied temporal and spatial information in the mesoscale which is not available from observations. Especially the lack of soundings at the eastern Adriatic coast appears to be a limiting factor when trying to really verify model results in the southern Adriatic, particularly with respect to the vertical bora structure at the coast as well as the offshore bora propagation. The results presented here call for further investigations of the nature of Adriatic storms, which, besides numerical studies, need more measurements, especially soundings over the Adriatic area.

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Figure 1. Subjective analysis of mean sea level pressure over Europe on 28 March 1995, 00 UTC. Isolines each 5 hPa. (From Meteorological Bulletin of Deutscher Wetterdienst).

Figure 2. Horizontal domain for the simulation. Grey scale according to the elevation of the (smoothed) model orography: 200, 400, 700, 1000, 1300, 1900 and 2500 m. Two-letter codes designate stations mentioned in the text: ZG-Zagreb, ST-Split, PL-Palagruža. The line AB marks a cross section presented in Figure 9.
Figure 3. 24-hours difference between the mean sea level pressure forecast in control experiment at 6 UTC on 27 and 28 March 1995. Isolines each 4 hPa, with negative values dashed. Maximum and minimum pressure fall noted with 'H' and 'L', respectively. Full model domain is presented.
Figure 4. Mean sea level pressure and 10 m wind forecast after 24 (a), 30 (b) and 36 hours (c) of model integration in the control experiment, valid at 00, 06 and 12 UTC 28 March 1995, respectively. Isolines each 2 hPa, wind arrows at every third grid point. Wind scaling presented in Figure 4a is the same for the rest of the figures.

Figure 5. Objective analysis of mean sea level pressure on 28 March 1995, 12 UTC. Domain is the same as in Figure 4, isolines each 2 hPa. (From ARPEGE system of Météo-France).
Figure 6. Mean hourly values of mean sea level pressure (a), temperature (b), wind direction (c) and speed (d) measured at Split coastal station, compared to the outputs from the control experiment at the closest grid point.

Figure 7. 30-hours forecast of potential temperature in control experiment at 700 hPa, valid at 06 UTC, 28 March 1995. Isolines each 2 K, potential temperature minimum noted with 'C', maximum with 'W'.
Figure 8. 30- (a) and 36-hours (b) forecast of wind at 925 hPa in the control experiment, valid at 06 and 12 UTC 28 March 1995, respectively. Isotachs each 5 m/s, starting at 15 m/s, wind arrows at each fourth grid point. Wind speed above 30 m/s is shaded. Values of local maxima and minima are printed.

Figure 9. Cross section of the wind speed in the control experiment along the line AB of Figure 2, valid at 12 UTC, 28 March 1995. Isolines each 4 m/s.
Figure 10. Mean sea level pressure and 10 m wind forecast after 36 hours of model integration in the experiment without Dinaric Alps, valid at 12 UTC 28 March 1995. Isolines each 2 hPa, wind arrows at each third grid point. To be compared with Figure 4c.

Figure 11. As in Figure 7, but for the experiment without Dinaric Alps.
Figure 12. As in Figure 8b, but for the experiment without Dinaric Alps.

Figure 13. (a) Mean sea level pressure difference between the control and 'no Dinaric Alps' experiment after 36 hours of integration, valid at 12 UTC, 28 March 1995. Isolines each 4 hPa, with negative values dashed.

(b) Difference of 850 hPa geopotential height between the control and 'no Dinaric Alps' experiment after 36 hours of integration, valid at 12 UTC, 28 March 1995. Isolines each 10 gpm, with negative values dashed. Null isoline is not drawn.
Figure 14. As in Figure 10, but for the experiment without Apennines.

Figure 15. As in Figure 8b, but for the experiment without Apennines.
Figure 16. 36-hours forecast of wind at 700 hPa in the control (a) and the dry experiment (b), valid at 12 UTC 28 March 1995. Isotachs every 5 m/s, starting at 15 m/s, wind arrows at every fourth grid point. Values of local minima and maxima are printed.