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A CASE STUDY OF A COLD AIR OUTBREAK ON 20 APRIL 1997 OVER CROATIA

Intenzivni prodor hladnog zraka nad Hrvatsku 20. travnja 1997.

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Abstract: This paper presents the weather situation on 20–23 April 1997, which was one of the strongest cold outbreaks ever recorded in April in Croatia. The processes leading to extremely low temperatures and heavy snowdrifts in the Dalmatian inland occurred on the front line between a polar air outbreak over central Europe and a deepening Mediterranean cyclone approaching the Adriatic. The genesis of a mesoscale vortex in the Adriatic has been diagnosed with the aid of satellite imagery and a high-resolution numerical model. The analysis of surface data has shown how the frontal system from the north slowed down over the Dinaric Alps and at mid-Adriatic, where the cyclogenetic process took place. The analysis of the vertical cross-sections produced using the rawinsonde data and the numerical model outputs have shown that the model successfully reproduced the intensity and time changes of the various meteorological fields. In particular, the model successfully reproduced a mesoscale cyclone developed in the lower troposphere over the southern Adriatic on 23 April.

Key words: cold front, mesoscale processes, numerical modelling, Dinaric Alps, Adriatic

Sažetak: Rad prikazuje vremensku situaciju od 20. do 23. travnja 1997, koja predstavlja jedan od najjačih zabilježenih travanjskih prodora hladnog zraka nad Hrvatsku. Procesi koji su uzrokovali izvanredno niske temperature i nanose snijega u Dalmatinskoj zagori posljedica su frontalnih procesa povezanih s prodorom polarnog zraka nad središnju Europu i ciklonom koja se razvijala nad Sredozemljem. Upotrebom satelitskih slika i numeričkog modela visokog razlučivanja dijagnosticiran je razvoj ciklone srednjih razmjera nad Jadranom. Analiza prizemnih podataka pokazala je usporavanje frontalnog sistema iznad Dinarida i srednjeg Jadrana gdje dolazi do procesa nastajanja ciklone. Analiza vertikalnih presjeka upotrebom sondažnih podataka i rezultata numeričkog prognostičkog modela pokazala je da je model uspješno prognozirao vremenski slijed atmosferskih procesa nad Dinaridima i Jadranom. Posebno je važna sposobnost upotrebljenog modela da reproducira razvoj mezoskalne ciklone nad južnim Jadranom 23. travnja.

Ključne riječi: hladna fronta, mezoskalni procesi, numeričko modeliranje, Dinaridi, Jadran

1. INTRODUCTION

Compared to the 30-year (1961–1990) average, April 1997 was a relatively cold month, with two distinct minima on the average daily temperature course. Both of them were lower than the two standard deviations of the 30-year average, the criteria usually used to describe extremely cold weather. The first minimum occurred on 16 April, when an extraordinarily cold upper-level cyclone was centred over the Balkan peninsula. The tem-

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perature at 500 hPa level dropped to –40°C. Snow was recorded at higher altitudes in Dalmatia, even on the islands (i.e. the island of Brač). The second cold outbreak at the beginning of the third decade first hit the northern parts of Croatia and then spread southward to the already cold Dalmatia. On 22 April, traffic through the Lika and Gorski Kotar regions was disrupted due to heavy snow and severe *bura* gusts. Extremely low temperatures were recorded all around the country. In Osijek, for example, the average daily temperature on 21 April was lower by 10.6°C compared to the 30-year average. More to the southwest, at Ogulin, the maximum daily temperature reached 1°C, a value 14.8°C lower than the 30-year average. The same day, 21 April 1997, was the day with the absolute minimum average daily temperature ever recorded at the Zagreb-Grič station, where regular meteorological measurements started in 1861. This extraordinarily cold weather lasted for a few days, accompanied by snow and rain showers. It might be worth mentioning the memorable, although non-meteorological, fact that buses carrying thousands of people were blocked for many hours by the snowdrifts in the Dalmatian hinterland.

This paper presents the processes leading to this second cold outbreak. The investigation was motivated by a general effort to study the mesoscale environment in which severe weather events in Croatia develop and by a significant lack of understanding of the local effects of fronts to the Dinaric Alps arriving from the north.

Both observational evidence and numerical results indicate that the interaction of the Dinaric Alps with a cold front plays a decisive role in the occurrence of weather events typical for Croatia. These include the strong *bura* wind, often accompanied by a low-level jet over the Dinaric Alps close to the coast, mesoscale cyclonic circulation in the Adriatic resulting from the interaction of the synoptic flow with the Alps and the Dinaric Alps, enhanced alongshore pressure and temperature gradients, the strong *jugo* wind in the southern Adriatic ahead of the front. Numerical modelling studies have shown that the Dinaric Alps, through their upstream blocking, have a dominant influence on the mesoscale development over the Adriatic (Brzović, 1997). A typical characteristic induced by the Dinaric Alps is an isalobaric maximum propagating on the eastern side of the Dinaric Alps while a mesoscale cyclone moves along the Adriatic sea channel. In the most intense cases, the pressure increase upstream of the Dinaric Alps can be three times as large as the pressure fall leading the system over the Adriatic. It is desirable to check whether and how the extreme cold weather in the last decade of April 1997 in Croatia fits the existing synoptic view and numerical results. Special emphasis in this study is given to the following issues:

(i) a detailed documentation of the synoptic-scale environment and mesoscale development, taking into account all available routinely collected data;

(ii) a clarification of whether a secondary cyclogenesis in the Adriatic occurred and, if so, whether it could be attributed to the influence of the Dinaric Alps on the cold front and whether a mesoscale model could reproduce it;

(iii) assessment of the relative importance of synoptic scale forcing and the Dinaric Alps orography upon the mesoscale development over the Adriatic sea.

This work aims to contribute to the research of atmospheric fronts over the Adriatic region. *Bura* forecasting should also benefit from this study since a frontal passage is usually followed by the *bura* wind. Understanding frontal dynamics over the Dinaric Alps should lead to a better correlation of fronts and post-frontal *bura* strength as well as to a better understanding of how the mesoscale development evolves along the coast.

The organisation of this paper is as follows: Further details regarding related studies are given in Section 2. Section 3 is devoted to the analysis of the synoptic-scale environment and the description of the satellite view. In Section 4, the analysis of surface data and the vertical atmospheric structure triggering the event are presented. Section 5 deals with the outputs of a mesoscale model. Concluding remarks, together with the discussion of some inevitable shortcomings in this case study, are given in Section 6.

2. RELATION TO PREVIOUS STUDIES

In recent years, mesoscale meteorology over the Dinaric Alps and the Adriatic region has received increasing attention. Most studies have been devoted to the severe *bura* and *jugo* winds and the associated synoptic systems. So far, no particular study is known to have been devoted to the investigation of the influence of the Dinaric Alps on the frontal behaviour upstream and downstream of them, over the Adriatic. In the past, several authors studied fronts passing north of the Dinaric Alps: Lalić (1959) and Čadež (1964) prepared climatological analysis of the fronts passing over former Yugoslavia. Both found that cold fronts are better pronounced in the eastern parts (nowadays Yugoslavia). The fronts over Slovenia were analysed by Petkovšek (1964, 1965), who noticed the influence of the humid southwesterly winds from the Mediterranean ahead of the front resulting in an increase in precipitation over Slovenia, when compared to the northern Alpine region. Bajić (1984) studied cold outbreaks over northeastern Croatia using 10-year climatological data collected at Zagreb-Grič and Zagreb-Maksimir. She found that the strongest cold air outbreaks at the surface usually do not coincide with the passage of the tropospheric frontal zone but occur after its passage. The main characteristic of such cases is a pseudo-frontal zone characterised by a strong fall in equipotential temperature. The zone occupies the lowest 2–3 km of the troposphere and it is related to a change in wind direction to NE. It has been also noticed that the upper-level frontal zone has different characteristics in cases with and without precipitation. However, none of the above studies addressed the question of what happens to the front after it reaches the Dinaric Alps. The manifestation of fronts arriving to the Adriatic coast from the north has not yet been specifically addressed, either.

A well-known surface front analysis over this area is a 70-year old analysis by Bergeron (from 1928), which shows a cold front deformed due to the orography of the Alps, the Dinaric Alps and the Apennines. In such strong blocking cases, cold air can enter the Mediterranean only through the Rhône valley on the western side of the Alps or as a *bura* flow across Slovenia and the northern Adriatic. Steinacker (1981, 1987) provided isochrones of different cold fronts crossing the Alps and the surrounding orography. His analyses clearly show that cold fronts slow down and deform cyclonically over the Dinaric Alps and the Adriatic (Fig. 1). The eastern branch of the front remains over the Dinaric Alps whereas its other part, which crosses the western Alps and, eventually, the Apennines, approaches the Adriatic from the west. In the case of total blocking by the Alps, the NE (*bura*) flow spreads deeper over the Adriatic and central Italy.

A higher spatial and temporal resolution of radio-soundings during the Alpine Experiment (ALPEX) brought about the first analyses of upper-level fronts over the Alps. It was suggested that in the lee of the Alps another deformation of the surface front can take place below the faster-progressing upper-level front. This, in turn, causes further deceleration of the surface front (Steinacker, 1987).

Isochrone analyses, like those of Steinacker, critically depend on network density. Therefore, lack of similar recent analyses for the Dinaric region is not surprising when taking into account the density of measurements. Nevertheless, recent numerical simulations, with and without orography (Brzović, 1999), have shown that the absence of the Dinaric Alps would lead to a much faster propagation of cold fronts to the east. The same numerical results, as well as the analysis of data collected during the ALPEX (Cacciamani et al., 1984), have shown that the Dinaric Alps induce significant pressure and temperature perturbation in the lower troposphere. Both studies found that the pressure perturbations induced by the Apennines is smaller than that induced by the Dinaric Alps, while the incoming flow is substantially modified downstream of the first ridge.

A cold air outbreak in the upstream region of the Dinaric Alps is accompanied by a pressure nose on their northern part (Tutiš and Ivančan-Picek, 1991). The pressure difference across the narrow northern Dinaric Alps can be greater than 10 hPa/50 km and it is highly correlated with pressure drag, as computed by Tutiš and Ivančan-Picek (1991). Pressure drag maxima during the ALPEX period were always related to periods of *bura*. An impor-

a)
b)
c)

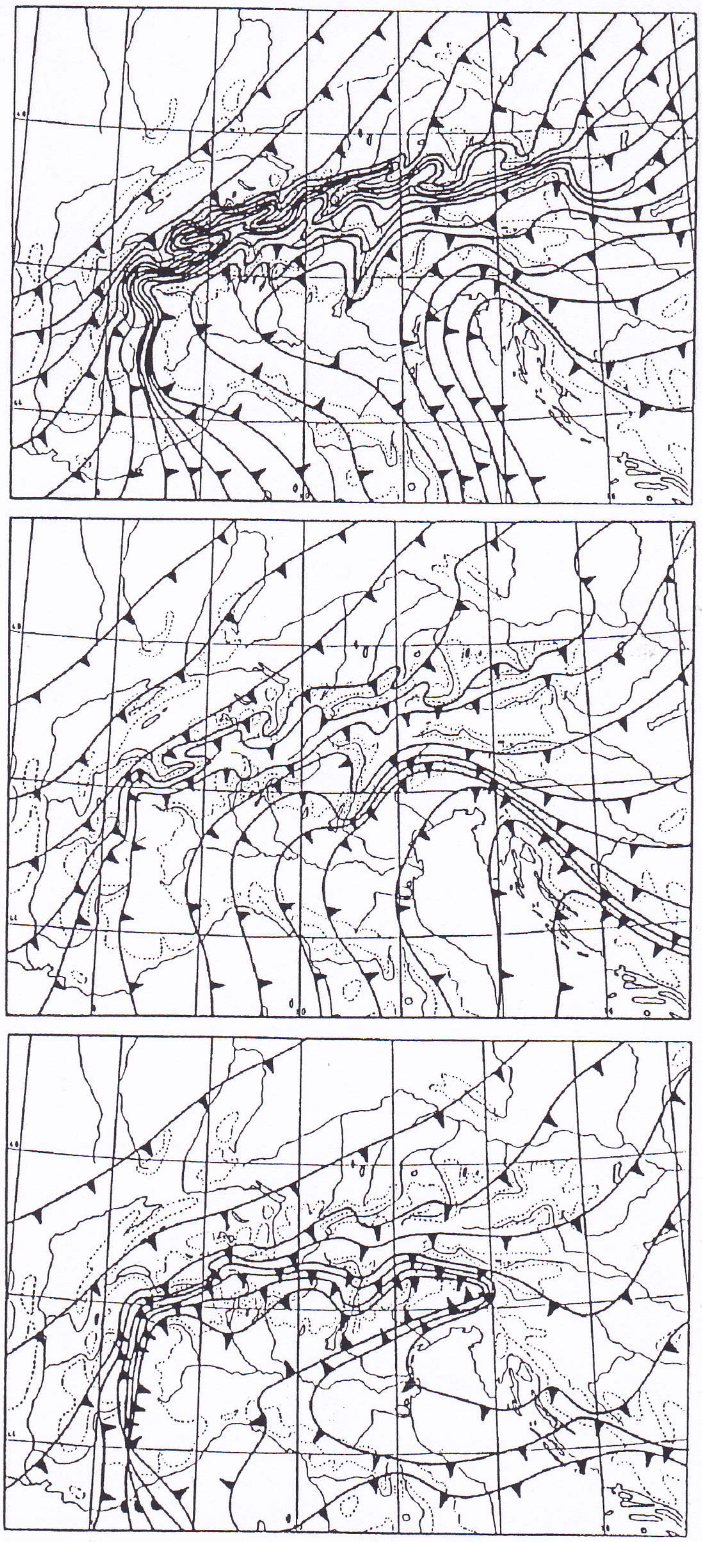

Figure 1. 3-hourly isochrones of a slowly moving cold front between 23 June 1978, 06 UTC and 25 June 1978, 06 UTC (a), a very intense cold front between 2 May 1979, 00 UTC and 3 May 1979, 12 UTC (b) and 6-hourly isochrones of a cold front in the case of total blocking by the Alps between 4 March 1982, 00 UTC and 5 March 1982, 18 UTC (c). (from Steinacker, 1987)

Slika 1. 3-satne izokrone spore hladne fronte tijekom razdoblja od 23. lipnja 1978, 06 UTC do 25. lipnja 1978, 06 UTC (a), 3-satne izokrone intenzivne hladne fronte tijekom razdoblja od 2. svibnja 1979, 00 UTC do 3. svibnja 1979, 12 UTC (b) i 6-satne izokrone hladne fronte u slučaju potpunog zaustavljanja zraka zbog Alpa tijekom razdoblja od 4. ožujka 1982, 00 UTC do 5. ožujka 1982, 18 UTC (c). (preneseno iz Steinacker, 1987) tant remaining question is the relationship between cold fronts over the Dinaric Alps and the cyclogenesis in the Adriatic. The results of numerical simulations hint at the decisive role played by orography in the maintenance of cyclones in the Adriatic. Orographic influence is visible in a high-low couplet over the Dinaric Alps and in severe winds along the coast following the cyclone. Sensitivity studies, described in Brzović (1999), confirmed that the mid-Adriatic cyclone is an orographic lee cyclone with respect to the Dinaric Alps, although it usually originates as a cyclone in the lee of the Alps. However, the role of frontal processes in the development of cyclones in the Adriatic remains to be investigated.

3. SYNOPSIS OF THE EVENT

3.1. Synoptic description

The cold outbreak on 20 April 1997 occurred in relation to the macroscale circulation between an anticyclonic system in the northern Atlantic, expanded throughout the troposphere, and a deep cyclonic system over Russia (Fig. 2). Between the two systems, air of polar origin progressed toward southern Europe. Later on, the anticyclonic system expanded to central Europe and the associated cold front reached the northwestern parts of Croatia in the midday hours of 20 April (Fig. 2a). Another system, whose development influenced weather in Croatia during this period, was a cyclone developing in the southern Atlantic on 19 April. A day later, it moved to the western Mediterranean deepening further (Fig. 2a-b). The two frontal systems came together in the Alpine region in the afternoon of 20 April and a day later over Italy and the Adriatic sea. In the exceptionally baroclinic atmosphere over the Alps and the Mediterranean, the cyclone deepened by a further 15 hPa at the surface, to a minimum of 985 hPa at 12 UTC on 21 April (Fig. 2c). Cyclonic circulation occupied most of the western Mediterranean and the surrounding orography, vertically extending up to 300 hPa.

This cyclonic event could be regarded as an example of a typical Alpine-Mediterranean cyclogenesis that has been well studied from observational (i.e. Buzzi and Tibaldi, 1978), theoretical (i.e. Speranza et al., 1985) and modelling perspectives (i.e. Buzzi et al., 1994). The cyclone growth was due to baroclinic instability, i.e. a meridional temperature gradient, which is related to vertical shear. The role of convection, sensible heat and heat fluxes in most cases of cyclogenesis over the Mediterranean has been considered marginal or even negligible compared to the topographical influence during the initial stage of the development (i.e. Alpert et al., 1996). In the spring case considered the sea-atmosphere fluxes could not play a significant role. It is the strongest atmospheric baroclinicity at this time of year that favours such events. A 500 hPa level trough (figure not presented) and a pressure fall in the whole Mediterranean region suggest that in the case considered the whole orography "took part" in the process. Temperature gradients at RT500/1000 level were much larger than their climatological value, with greatest gradients over the Adriatic and the Dinaric Alps.

The subjective analysis in figure 2b gives a hint of a secondary mesoscale cyclone developing in the Adriatic on 21 April. Its development started as a wave in the cold front over the Dinaric Alps and the Adriatic. However, its further growth is relatively weak, spatially limited by the surrounding orography. The day after, on 22 April, a smaller Adriatic cyclone merged with the Mediterranean cyclone that moved from Italy to the northeast, the process being related to the weakening of the anticyclone in central Europe and the occlusion over Scandinavia on a synoptic scale (Fig. 2d).

3.2. Satellite diagnosis of mesoscale development

A further diagnosis of the development over the Adriatic is provided by the satellite imagery. The dominant feature of figure 3a is an elongated band of active frontal clouds, which extends from the Ligurian sea and northern Italy to central Europe. The overall cloud pattern demonstrates the intensity of the vertical development over the Mediterranean. Besides the broad cloud system of characteristic comma shape associated with the cyclone at that time centred near Sardinia, the tropospheric baroclinic zone over the western Mediterranean is also deformed in a comma shape. It is the area where a new upper-level cy-

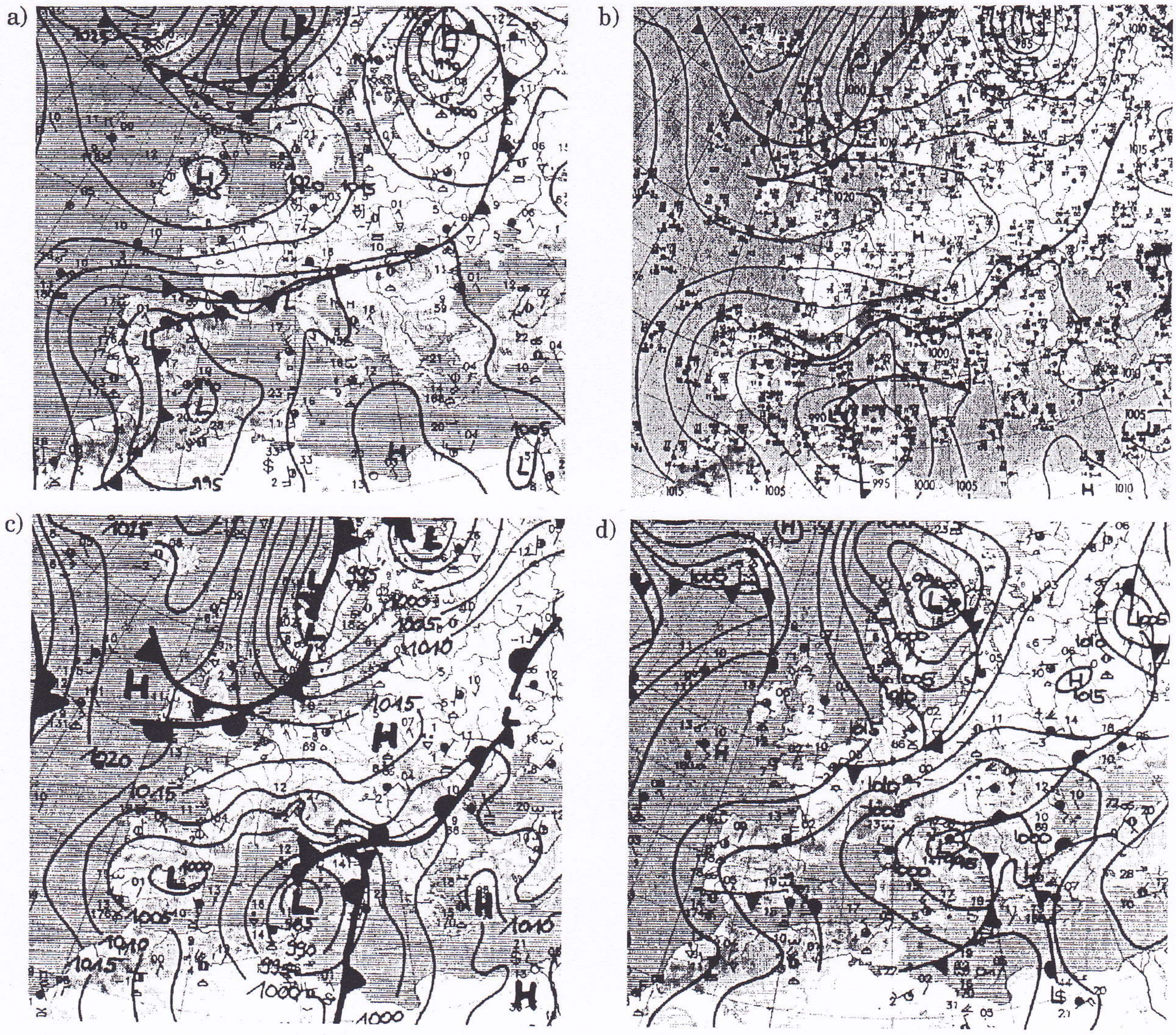

Figure 2. Subjective analysis of the mean sea level pressure over Europe on 20 April 1997, 12 UTC (a), 21 April 1997, 00 UTC (b), 21 April 1997, 12 UTC (c) and 22 April 1997, 12 UTC (d) (From Meteorological Bulletin of German Weather Service).

Slika 2. Subjektivna sinoptička analiza prizemnog polja tlaka nad Europom 20. travnja 1997, u 12 UTC (a), 21. travnja 1997, u 00 UTC (b), 21. travnja 1997, u 12 UTC (c) i 22. travnja 1997, u 12 UTC (d) (iz Meteorološkog izvještaja Njemačke meteorološke službe).

clone develops. The shape of the cloud system shows that the upper-tropospheric flow is in phase with the tropospheric cyclonic system. Due to the intensity of the macroscale system, the secondary cyclone over the Adriatic is hardly visible in figure 3a, except as a somewhat lighter area over the mid-Adriatic. On 22 April, the baroclinic system in the upper troposphere weakened significantly and moved to the northeast, as confirmed by the infrared satellite image in figure 3b. The centre of the system is located over the Adriatic. A visible satellite image at the same time (not shown), indicates a development of convective clouds in the lower troposphere over the Adriatic, as confirmed by records of showers and thunderstorms at several mid-Adriatic stations.

Whereas, on 23 April, the surface low in the synoptic pressure field was located over the Black sea, a part of the cyclonic system associated with the upper-level trough over the Adriatic and central Italy remained over this area (Fig. 3c). The intensity of the convective development during midday hours is nicely shown by the visible satellite image about

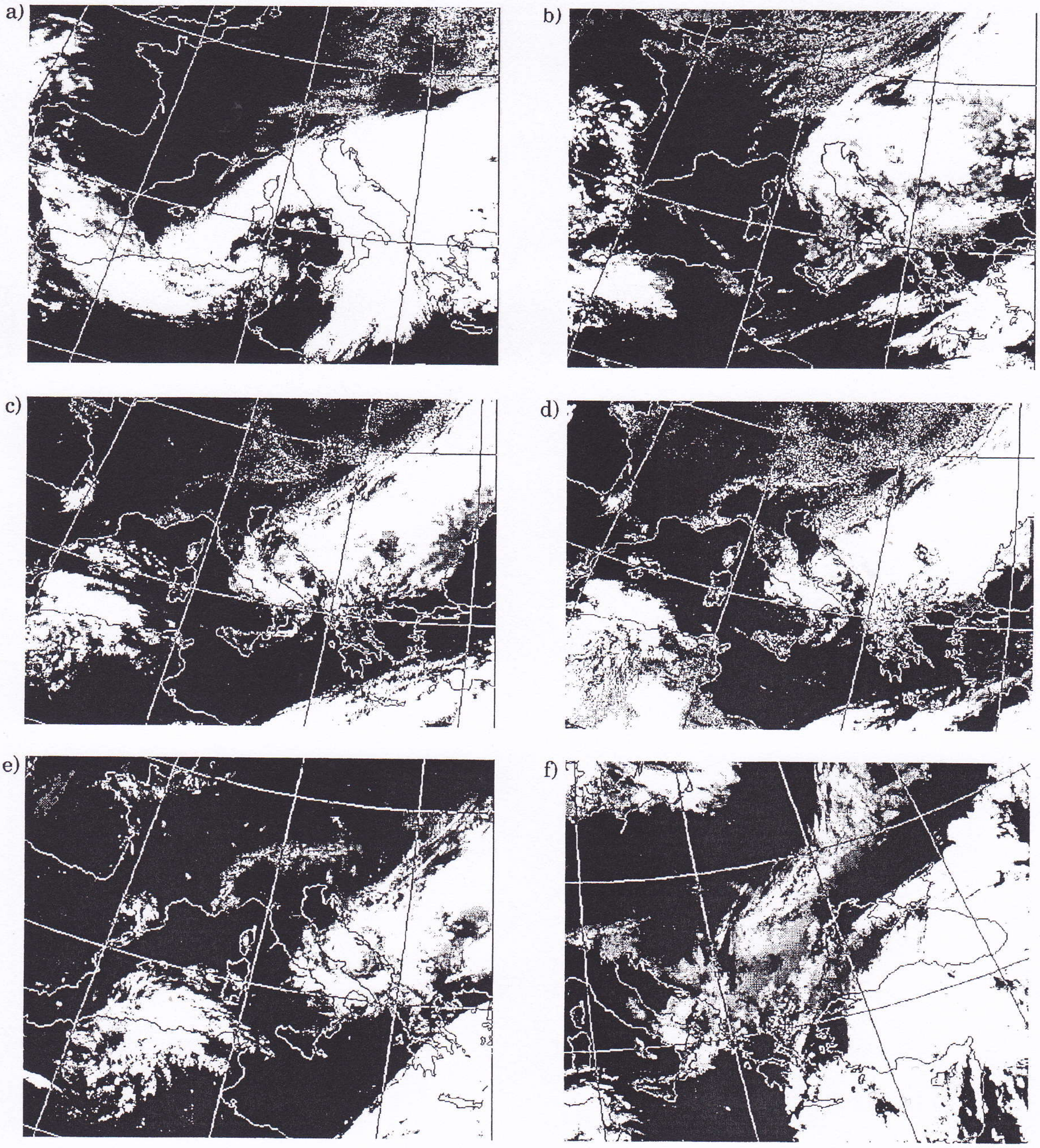

Figure 3. (a) NOAA satellite images in infra-red spectra on 21 April 1997, 13:13 UTC; (b) as (a), only for 22 April 1997, 13:02 UTC; (c) as (a), only for 23 April 1997, 12:52 UTC; (d) NOAA satellite images in visible spectra on 23 April 1997, 12:52 UTC; (e) as (a), only for 23 April 1997, 17:29 UTC; (f) as (a), only for 24 April 1997, 01:04 UTC.

Slika 3. (a) Infracrvena satelitska slika (NOAA, Kanal 4) 21. travnja 1997, u 13:13 UTC; (b) kao (a), ali za 22. travanj 1997, u 13:02 UTC; (c) kao (a), ali za 23. travanj 1997, u 12:52 UTC; (d) Vidljiva satelitska (NOAA, Kanal 2) 23. travnja 1997, u 12:52 UTC; (e) kao (a), ali za 23. travanj 1997, u 17:29 UTC; (f) kao (a), ali za 24. travanj 1997, u 01:04 UTC.

midday on 23 April (Fig. 3d). The vortex at the surface is indicated by the existence of the eye. The diameter of the vortex is very small – less than 200 km across. Such small-scale lows are strongly influenced by deep convection (Bader et al., 1995), which in this case lasted until the evening hours (Fig. 3e). By the end of the day, the system started to decay (Fig. 3f). In Section 4 it will be shown that this feature is not actually visible from the existing national meteorological network data. Therefore, in Section 5, a high-resolution numerical model will be employed to further explore the mesoscale development on 23 April.

4. MESOSCALE ANALYSIS OF SURFACE DATA

Time traces of temperature and pressure upstream and downstream of the Dinaric Alps at Zagreb and Split, respectively, reflect how the Dinaric Alps influence the atmospheric processes that control local climate (Fig. 4). A pressure minimum, recorded during the afternoon of 19 April at Zagreb, was of local character, not recorded at neighbouring stations and hard to diagnose due to the lack of other data sources for that period. Arrival of the main front around 10 UTC on 20 April was not abrupt as in the previously studied case of the front on 27 March 1995 (Brzović, 1997). Following frontal passage the most in-

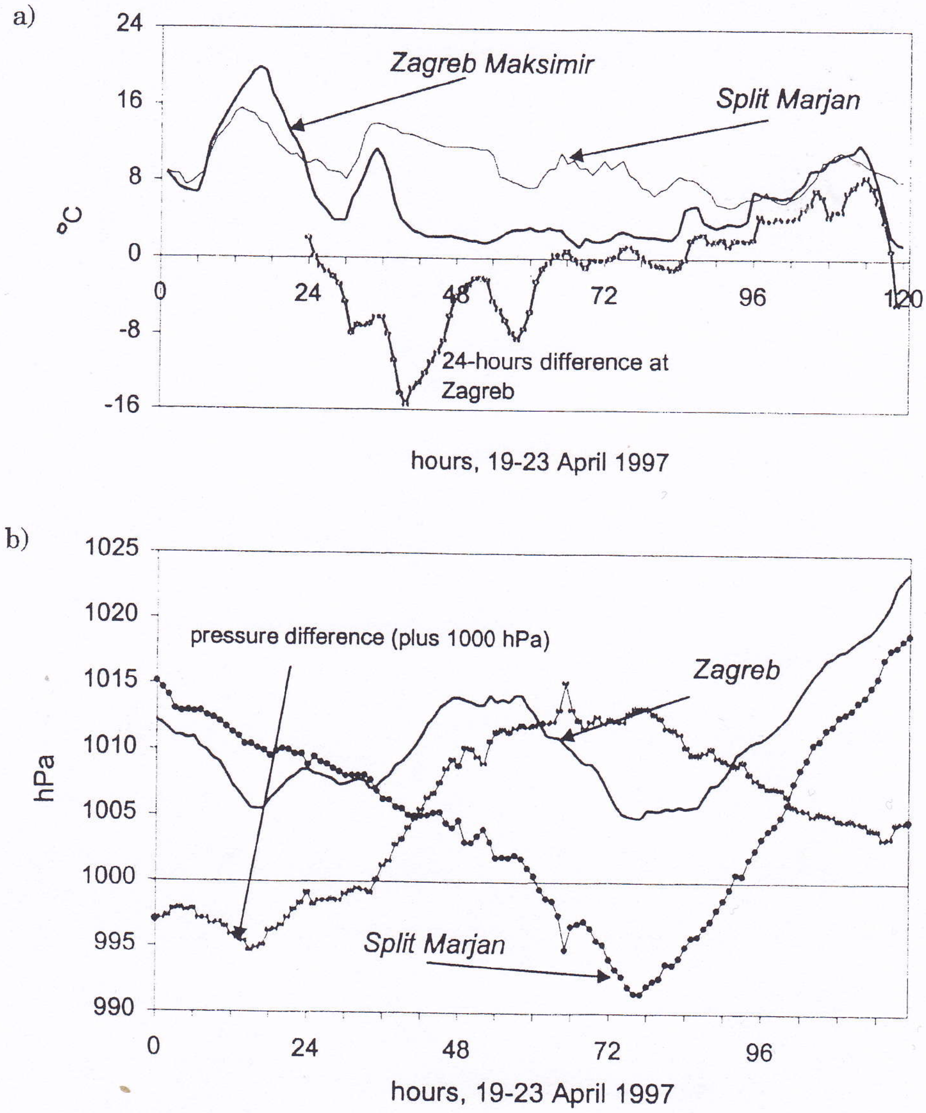

Figure 4. Time traces of mean hourly values of the air temperature at Split and Zagreb, and the 24-hour difference in temperature between the two sites, during the period 19–23 April 1997 (a), time traces of mean hourly values of mean sea level pressure at Split and Zagreb, and the pressure difference between the two sites, during the period 19–23 April 1997 (b).

Slika 4. (a) Vremenski hod srednjih satnih vrijednosti temperature zraka u Splitu i Zagrebu i 24-satna razlika temperature u Zagrebu u razdoblju od 19. do 23. travnja 1997, (b) Vremenski hod srednjih satnih vrijednosti tlaka zraka u Splitu i Zagrebu i razlika tlaka između njih (dodana na 1000 hPa) u razdoblju od 19. do 23. travnja 1997.

tensive cold outbreak in the northern part of Croatia occurred during the afternoon hours of 20 April. A NE flow replaced the NW flow ahead of the front. Temperature dropped by 5–10°C within a few hours. Figure 4a shows also the 24-hour difference in temperature at Zagreb, which illustrates the intensity of the cold outbreak. The average daily temperature dropped from 13°C on 19 April to 5.1°C on 20 April and to 2.3°C on 21 April, the already mentioned absolute April daily minimum recorded at the station. A further outbreak of cold air to the Adriatic was slowed down by the blocking effect of the Dinaric Alps. Therefore, pressure at Split continued to fall while the local temperature was only slightly disturbed. On the other side, the cold air outbreak at Split was neither so sudden nor so intensive as the one in northern Croatia because the weather in Dalmatia was already influenced by the upper-level cyclone over the Balkan peninsula and by another cyclonic system approaching from the western Mediterranean.

The frontal analysis in figure 2 depicts the synoptic-scale characteristics only. Hence, the modification of the front as it approached the Dinaric Alps cannot be captured by such an analysis. Such analyses also often underestimate the pressure gradients across the Dinaric Alps, as the one at 12 UTC on 21 April 1997 in figure 2c (if compared to stations data, figure not shown). A modified surface front arrived to the mid-Adriatic coast about 18 hours later than at Zagreb, as can be seen from the temperature record (Fig. 4a) as well as from the surface wind shift in figure 5. This figure has been obtained using all the synoptic and climatological data available at the moment and therefore represents up-to-date information on the wind field in the Adriatic. The figure shows a typical surface wind field over the Adriatic when a cold front arrives to the Dinaric Alps: southeastern *jugo* blows in the southern Adriatic inside the warm sector of a cyclone in the Mediterranean, while *bura* usually begins as the front passes over a particular locality. Such a structure of the wind field triggers local in-

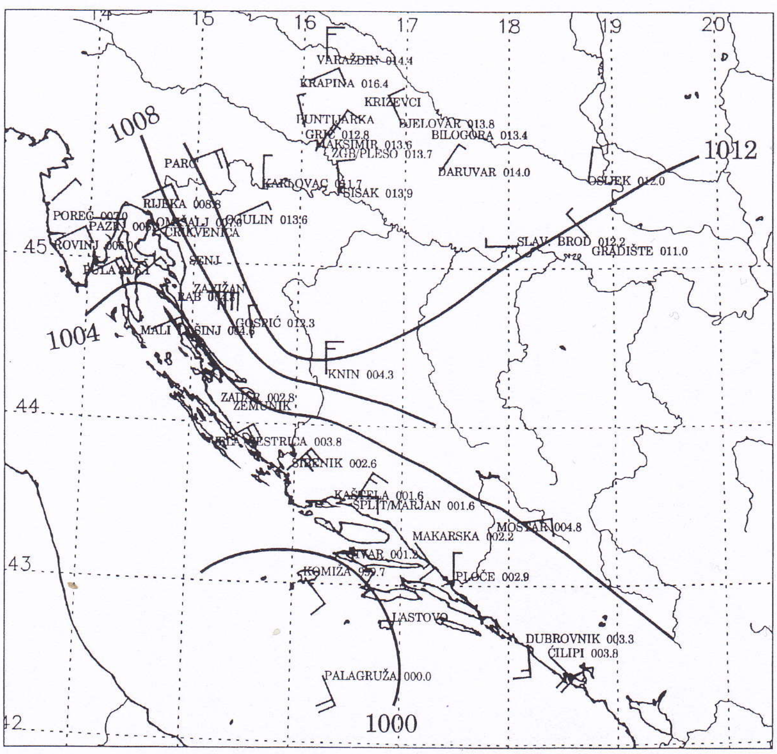

Figure 5. Surface analysis of wind and pressure over Croatia on 21 April 1997, 06 UTC. Isolines at each 4 hPa, pressure values printed without 1000 hPa.

Slika 5. Analiza prizemnog polja vjetra i tlaka 21. travnja 1997, u 06 UTC. Izolinije tlaka prikazane su u razmaku od 4 hPa, vrijednosti tlaka na razini mora ispisane su bez znamenke za 1000 hPa.

stabilities over the sea which may, depending on the large-scale flow, develop into a meso-ß cyclone. The most intense *jugo* cases bring large amounts of precipitation to the eastern Adriatic coastlands. An example of such a typical chain of events has been recently described and numerically simulated by Brzović and Strelec-Mahović (1998).

In many cases, it is difficult to document frontal passage over the Adriatic coast by using pressure records. Figure 4b confirms that the pressure record at Split was not significantly disturbed on 21 April. During the day, a pressure difference between the upstream region of the *bura* and Dalmatia established at the values of 10–12 hPa. This difference lasted until noon on 22 April, when the synoptic-scale system began to fill up and move out of the area. Surface analyses on 21 and 22 April (figures not shown) reveal a wind and pressure pattern almost identical to the one presented in figure 5 for 06 UTC on 21 April. This confirms that the front stopped in mid-Adriatic while intensifying, the process being related to the occlusion over Italy. The data at Dubrovnik (figure not shown) show a permanent temperature increase over the southern Adriatic during the afternoon and night of 21 and 22 April, until the morning hours of 23 April.

Arrival of the front at Split is clearly indicated by a sudden temperature drop around 06 UTC and by a change of wind direction. An analysis of equipotential temperature above the surface, often used to identify fronts in orographic regions (e.g. Buzzi and Alberoni, 1992) is not currently feasible for the Adriatic area due to the lack of upper-level data. This deficiency could be overcome by using mesoscale model outputs, as will be presented in Section 5.

The most pronounced temperature minimum at Split was in the afternoon of 21 April, related to the frontal intensification and cyclogenesis in the Adriatic. The temperature fall was reduced due to daily warming and the low-level advection of a warmer, humid air from the Mediterranean. Pressure continued to fall till the early morning hours of 22 April when the two cyclonic systems merged and the cyclone started to fill up in the Adriatic.

A more extensive analysis using other stations upstream and downstream of the Dinaric Alps additionally confirms a strong signal of the orographic influence of the Dinaric Alps slowing down or blocking the cold fronts arriving from the northwest. SYNOP reports show that only few stations on the northern Adriatic coast (i.e. Senj, Rijeka) recorded the arrival of the cold front in the late afternoon of 20 April in their pressure records. Another main minimum related to the movement of the mature cyclone to the east was recorded at all stations along the coast around 06 UTC on 22 April. This is the time of the maximum intensity of the process, when the centre of the cyclone was located in mid-Adriatic according to the SYNOP reports, which reported almost no wind area there. This result is in agreement with the existing analyses of the behaviour of cold fronts in the Alpine region (e.g. Steinacker, 1987), which have shown that cold fronts usually arrive to the northern Adriatic coast. However, their subsequent movement along the Adriatic sea channel to the southeast is related to the fact of whether or not a cyclogenetic process takes place in the Adriatic.

A zone of an enhanced north-to-south pressure gradient is also evident from the reports on wind, rain and snow. The maximum wind speed was recorded on the Dalmatian islands during the most intense cyclogenetic process on 21 April. Komiža registered of 31.3 ms^{-1} while the value of the maximum on Lastovo was 28.7 ms^{-1}, both from the ESE direction. Later on, the *bura* spread up to the mid-Adriatic coast where it reached its maximuml strength in the afternoon of 23 April, when the mesoscale convection over this area was the most active, as seen in Figures 3c–e. Combined wind and pressure records from the islands (figures not shown) show marked pressure changes and a decrease in wind speed at the time when the vortex passed over the particular station.

Figure 6 shows some of the routinely collected rain gauge records along the Adriatic coast. Such data have been already proved a valuable source of information for synoptic analyses on the mesoscale (e.g. Volkert, 1989) and provide additional information about the movement of the front. All investigated stations in the continental part of Croatia recorded rainfall accompanying the front during the first few hours of the afternoon of 20 April. Later on, precipitation turned into

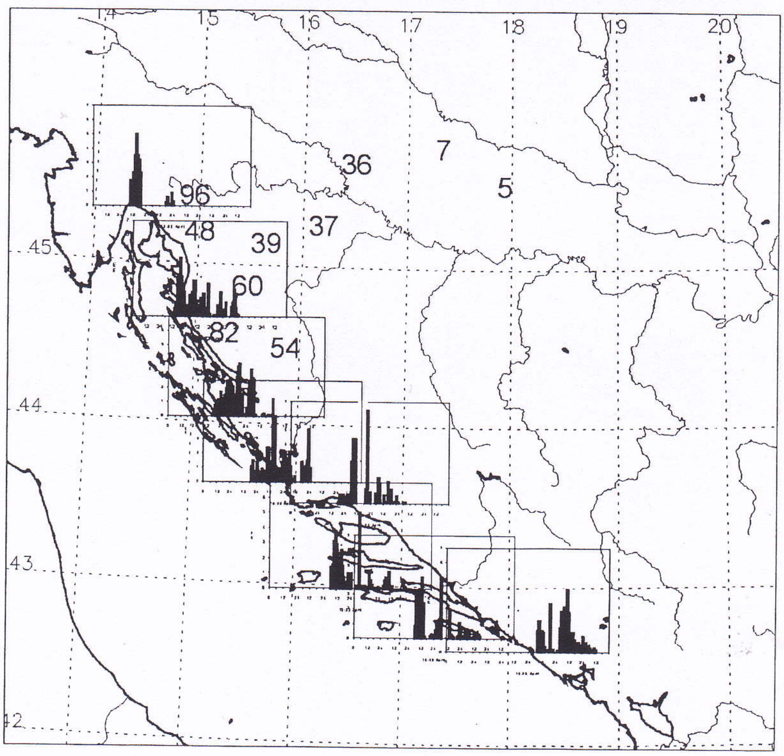

Figure 6. Precipitation histograms (mm) along the eastern Adriatic coast during the period 19–24 April 1997 and snow cover thickness (numbers) recorded at 06 UTC, 23 April 1997.

Slika 6. Histogrami razdiobe oborine (mm) uzduž obale tijekom razdoblja od 19. do 24. travnja 1997. i visina snijega izmjerena 23. travnja 1997, u 06 UTC.

snow. The location of the precipitation maximum on the coast was moving from northern Adriatic (on 21 April) to southern Dalmatia (on 23 April). The time distribution of precipitation confirms that the short precipitation interval on the northern Adriatic was related to the arrival of the front whereas the later, longer-lasting precipitation intervals were related to the downstream intensification of the front. The heaviest precipitation occurred on 22 April in the mid-Adriatic area of the Pelješac peninsula, Ploče and the Dalmatian hinterland.

The analysis presented in this Section shows that the surface data in Dalmatia, downstream of the Dinaric Alps, do not indicate the passage of cold fronts in a classical way. Exceptions are very intense fronts that quickly pass over Croatia within 12 hours as in the case of 27 March 1995 (Brzović 1995). In most cases, however, it seems that a frontal splitting occurs and that part of the front progresses along the Dinaric Alps further to the east while its other part crosses the mountain barrier and triggers downstream convective processes. This is not a new result because already the famous analysis of Bergeron showed that fronts propagate faster on the eastern side of the Dinaric Alps and eventually do not reach the coast. Similar conclusions could be drawn from the analysis done by Steinacker (1981, 1987). The diagnosis of the up-to-date surface data on the mesoscale is our contribution to the description of front behaviour.

5. VERIFICATION OF THE RESULTS OF A MESOSCALE MODEL

The numerical simulation results used are the operational results of the mesoscale model ALADIN/LACE. The model evolves from the joint international projects of the French meteorological service Météo-France and several national meteorological services (Members of the ALADIN international team, 1997, and references therein). The results of the model have been used operationally at the Meteorological and Hydrological Service of Croatia for the past four years. The model has already shown to be a very reliable tool for predicting cold outbreaks over Croatia (Brzović et al., 1997). The model results will be presented here to verify its ability to simulate wind fields in the Adriatic and, in particular, the mesoscale vortex in the southern Adriatic on 23 April, as diagnosed by the satellite imagery in Section 3.2. A further step in the model verification is a comparison of the vertical atmospheric structure, in particular the *bura* layer depth and strength and the frontal characteristics obtained from the model with real data. Due to the lack of upper-air measurements in the Adriatic, the vertical structure of the atmosphere obtained from the model can be verified only against the data of the two closest observatories: Zagreb and Udine. These model outputs will be compared generally to the results presented by Jurčec and Visković (1994) and Jurčec and Brzović (1995), where the vertical atmospheric structure using rawinsonde data at different locations was studied. All studied cases were associated with a frontal passage from the north and the *bura* behind it. A distinct speciality of the second of the mentioned studies is the representation of the vertical atmospheric structure over the Adriatic, due to number of soundings available at Split greater than usual.

The model outputs presented in figures 7 and 8 are the result of two operational model runs. The first started on 20 April, 00 UTC and the second at 00 UTC on 22 April. Each lasted for 48 hours. The horizontal grid resolution was around 14 km, with 27 levels in the vertical direction. Figure 7 presents the model forecast over the Adriatic after 30 hours of integration, valid at 06 UTC, 21 April 1999. Comparison with figure 5, which shows surface data measured at the same time, reveals that the model captured the main flow features well: the position of the front in mid-Adriatic, south-easterly winds along the southern Adriatic coast, the *bura* flow covering the northern Adriatic area, a partial blocking of the flow upstream of the Dinaric Alps and pressure gradients across it. But the *bura* speed is overestimated in the region of Kvarner and Istra up to 50% and surface pressure in the southern Adriatic is somewhat underestimated (by 2 hPa). An overview of the model output at subsequent times (figures not presented) shows that the front remained across the Dinaric Alps and the Adriatic during the whole day on 21 April. Two days later, when the main synoptic system moved to the north-east, the ALADIN/LACE run from 00 UTC on 22 April was able to reproduce a mesoscale cyclone in the southern Adriatic, seen by the NOAA satellite in figure 3. Figure 8 shows the Adriatic low weakening during the day, on 23 April. The surface pressure field shows a structure typical of cyclonic situations over the southern Adriatic: the separation of low pressure centres on either side of the Apennine peninsula, referred to by Brzović and Jurčec (1995) as "twin-cyclones". This picture shows the effect of the orography of the Apennine peninsula in splitting the surface pressure and wind field of a larger cyclonic system into two parts although the main centre, in this case, was situated in the Adriatic. At 12 UTC on 23 April (Fig. 8c) the centre of the meso-cyclone was located

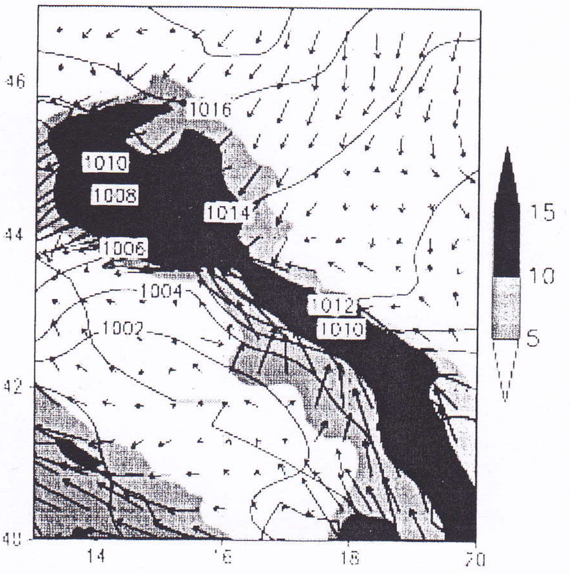

Figure 7. Mean sea level pressure forecast and 10 m wind forecast after 30 hours of integration in the ALADIN/LACE model, valid at 06 UTC on 21 April 1997. Wind magnitude is shadowed each 5 ms^{-1}. Pressure isolines are drawn each 2 hPa, wind arrows at each third grid point. Only part of the model domain is presented.

Slika 7. Prognoza tlaka na razini mora i vjetra na 10 m visine nakon 30 sati integracije u modelu ALADIN/LACE, rezultati važeći za 06 UTC 21. travnja 1997. Brzina vjetra je osjenčena svakih 5 ms^{-1}. Izolinije tlaka su prikazane u razmaku od 2 hPa, a vjetar u svakoj trećoj točki mreže. Prikazan je dio područja integracije modela.

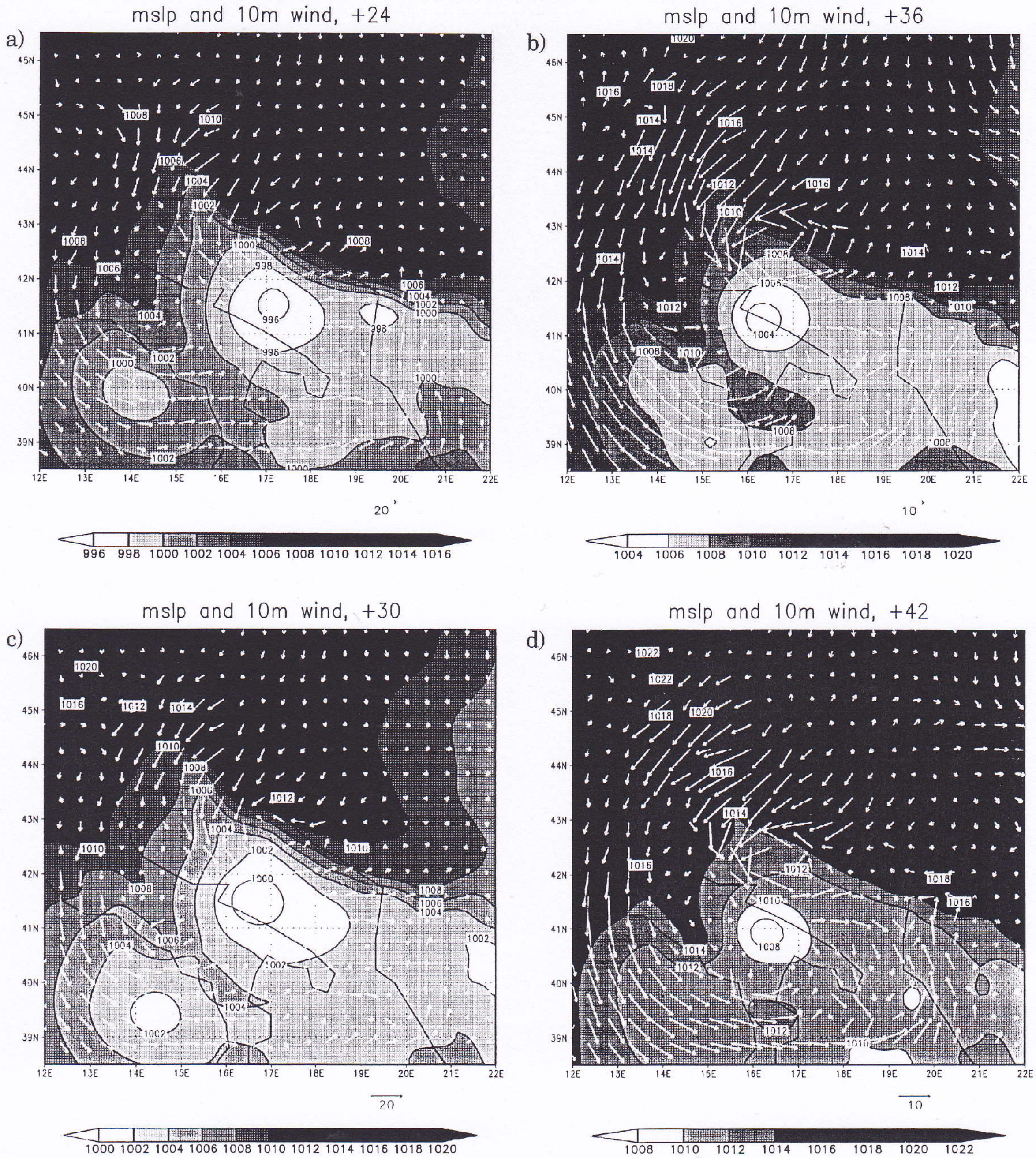

Figure 8. Mean sea level pressure forecast and 10 m wind forecast after 24 hours (a), 30 hours, (b) 36 hours (c) and 42 hours (d) of integration in the ALADIN/LACE model, valid at 00 UTC (a), 06 UTC (b), 12 UTC (c) and 18 UTC (d) on 23 April 1997. Pressure isolines are drawn each 2 hPa, wind arrows at each third grid point. Only part of the model domain is presented.

Slika 8. Prognoza tlaka na razini mora i vjetra na 10 m visine nakon 24 sata (a), 30 sati (b), 36 sati (c) i 42 sata (d) integracije u modelu ALADIN/LACE, rezultati važeći za 00 UTC (a), 06 UTC (b), 12 UTC (c) i 18 UTC (d) 23. travnja 1997. Izolinije tlaka su prikazane u razmaku od 2 hPa, a vjetar u svakoj trećoj točki mreže. Prikazan je dio područja integracije modela.

near the Italian coast in the southern Adriatic. There is a significant pressure difference of 12 hPa established across the Dinaric Alps, while the high-pressure centre progresses on its eastern side. The vortex centre in the surface pressure field does not coincide with the centre of wind rotation, a feature noticed in previous data analyses over the larger Alpine area (Gomis et al., 1990) as well as over the Adriatic (Jurčec et al., 1996). In these papers, the authors explain this fact as a consequence of organized ageostrophic flow, which, together with the associated geostrophic adjustment process, is a possible energy source for mesoscale wave disturbances.

Figure 9 shows the time vertical cross-section of wind speed at the two rawinsonde stations, Zagreb and Udine, during the four-day period of 20–23 April 1997. The most important characteristic of a wind field is the presence of the sub-polar jet on 20 and 21 April. The core of the jet occupies the whole upper troposphere with maximum speed reaching over 50 ms^{-1}. The structure of the isotachs in the lower troposphere shows that the passage of the front was accompanied by a short period of wind intensification at both localities. Behind the front, isolines are vertically stretched while the low-level northeasterly wind intensifies again. This is more visible at Zagreb and represents a *bura*-feeder flow, a regular feature of Zagreb's sounding during intense *bura* cases in winter (i.e. Jurčec and Brzović, 1995). The front at Zagreb is well indicated also in figure 9c, by the equipotential temperature isolines that lift up steeply during the afternoon of 20 April. The temperature field shows that the cold outbreak was limited to the lowest 2 km of the atmosphere. Above this height, warm advection from the Mediterranean induced warming.

The vertical atmospheric structure given in figure 9 serves as a verification of the information obtained from the model, shown in figure 10. The data presented were extracted from the model at the grid point closest to the locations of the Zagreb and Udine observatories. Vertically, the data contain 27 horizontal model levels while their time frequency is three hours. A comparison of the two figures shows that the model forecast reasonably well the main features of the tropospheric wind field such as the jet intensity, the double maxima of the jet, wind direction and its shift as well as post-frontal low-level wind intensification. However, the low-level wind maximum at Zagreb seems to be overestimated and longer-lasting than in reality. It has to be mentioned that the rawinsonde data were available only every 12 and 6 hours at Zagreb and Udine, respectively, so the discrepancy between the model and reality could partially result from the observation scarcity. The thicker and stronger upstream layer of the *bura*-feeding flow probably caused *bura* in the northern Adriatic harbour of Rijeka to be stronger in the model than in reality (Fig. 10c). According to the model's results wind at the surface is stronger than recorded while the low-level jet is located at a height of 1 km. This overestimation of the surface *bura* speed can be seen also in figure 7 (as compared to figure 5) for the broader region of the northern Adriatic. This might be related, for instance, to the model's inadequate vertical

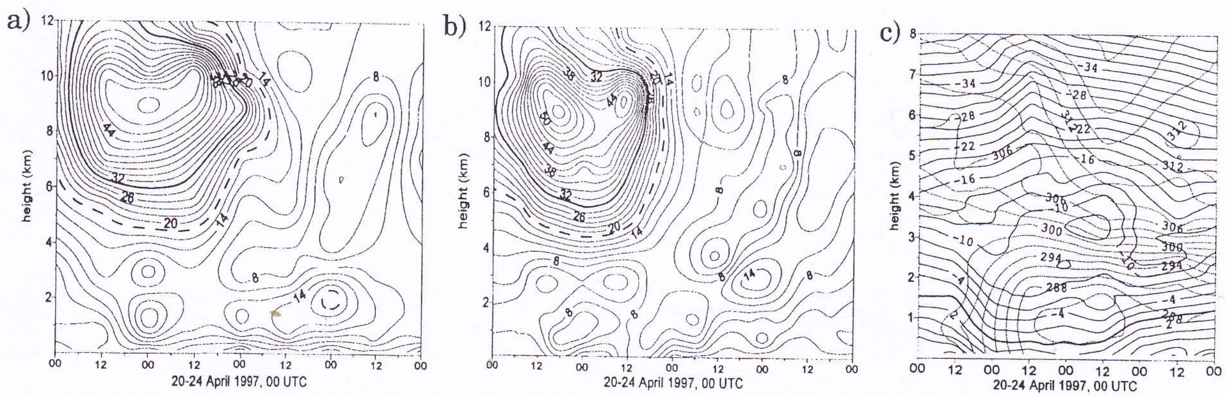

Figure 9. Vertical time cross-sections of wind speed over Zagreb (a) and Udine (b) and cross-section of temperature and equivalent potential temperature over Zagreb (c) during the period 20–24 April 1997, 00 UTC. Dashed lines in figures (a) and (b) correspond to 18 m/s, criteria used for the severe wind.

Slika 9. Vremenski vertikalni presjek brzine vjetra iznad Zagreba (a) i Udina (b) te presjek temperature i ekvivalentne potencijalne temperature iznad Zagreba (c) u razdoblju od 20. do 24. travnja 1997, 00 UTC. Crtkana linija odgovara brzini od 18 m/s, kriteriju za olujni vjetar.

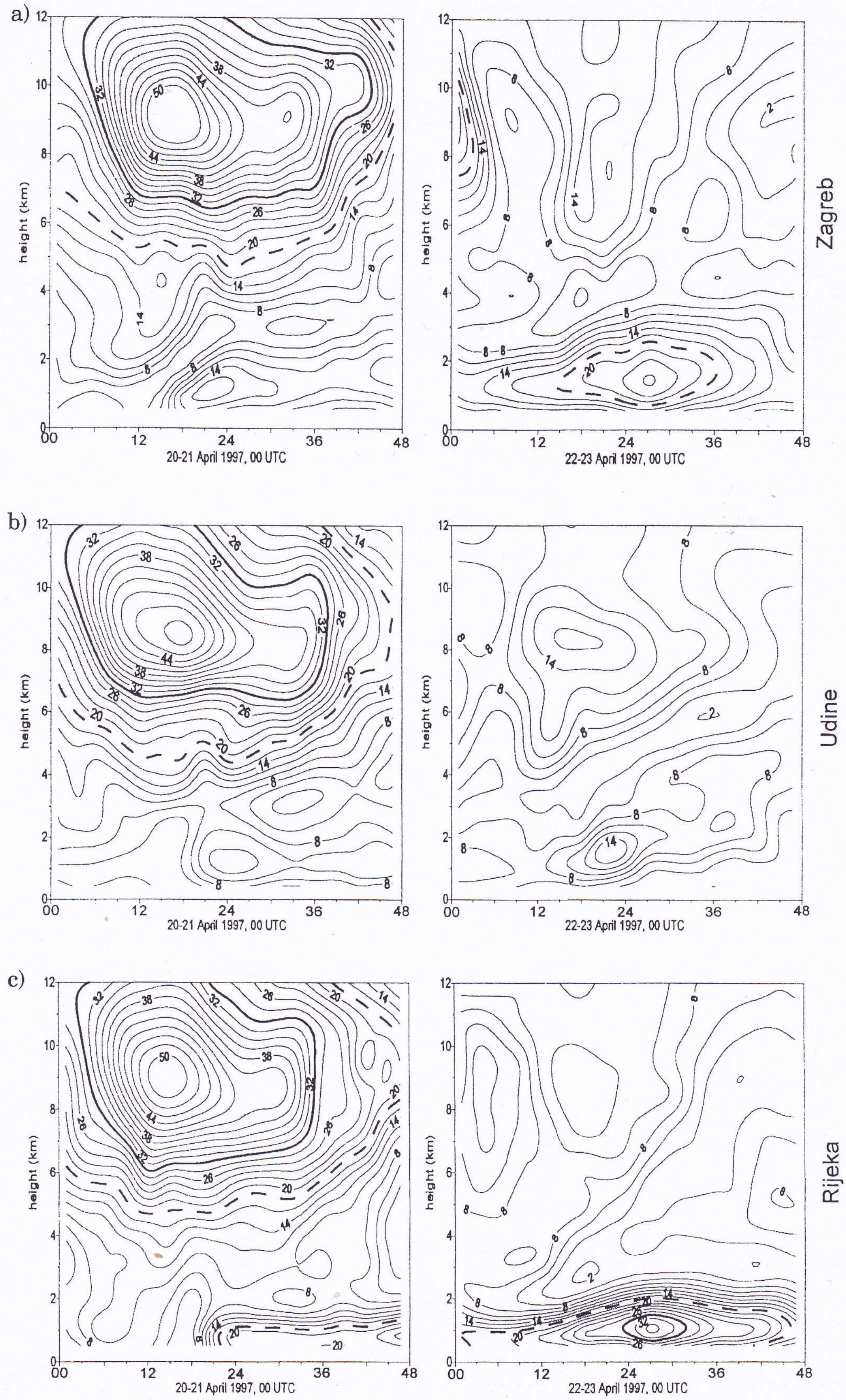

Figure 10. Prognostic vertical time cross-sections of wind speed over Zagreb (a), Udine (b) and Rijeka (c) during the periods 20–22 April 1997, 00 UTC and 22–24 April 1997, 00 UTC.

Slika 10. Prognostički vremenski vertikalni presjeci brzine vjetra iznad Zagreba (a), Udina (b) i Rijeke (c) u razdobljima od 20. do 22. travnja 1997, 00 UTC i od 22. do 24. travnja 1997, 00 UTC.

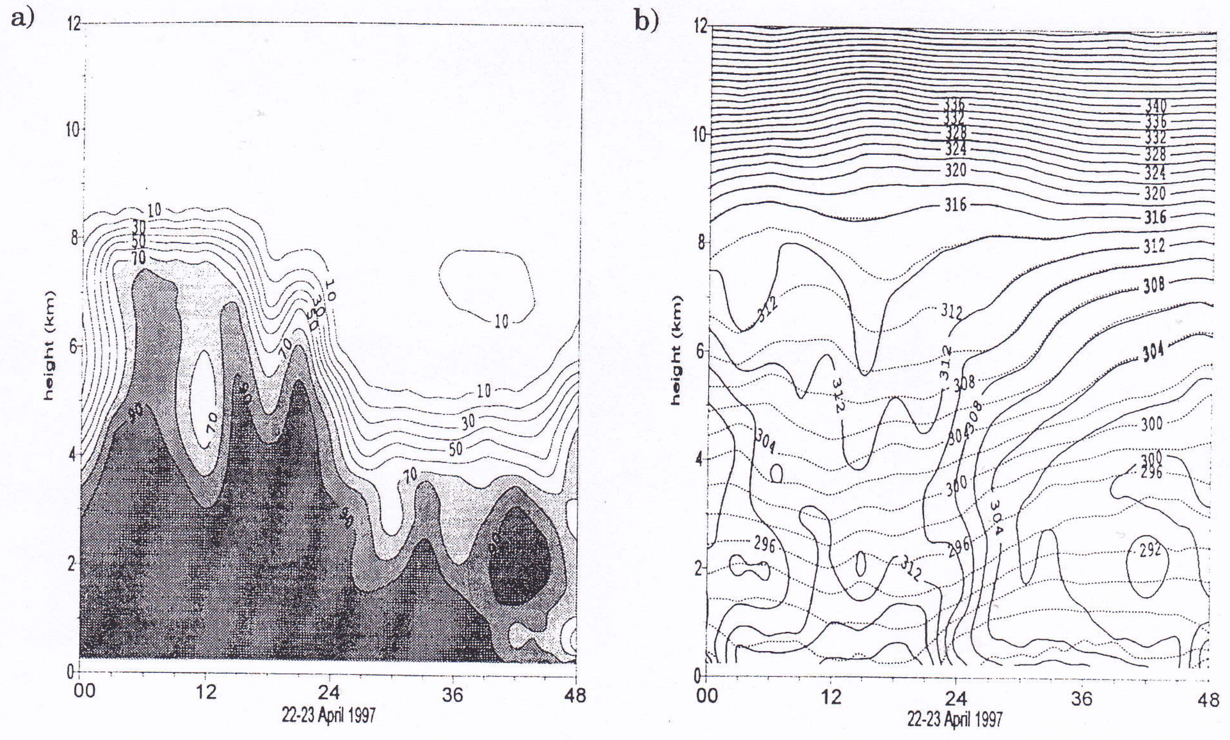

Figure 11. Prognostic vertical time cross-sections of relative humidity (a) and the potential and equivalent potential temperature (b) over Dubrovnik during the period 22–24 April 1997, 00 UTC.

Slika 11. Prognostički vremenski vertikalni presjeci relativne vlažnosti (a) te potencijalne i ekvivalentne potencijalne temperature (b) iznad Dubrovnika u razdoblju od 22. do 24. travnja 1997, 00 UTC.

resolution and/or turbulence parametrization sheme.

Atmospheric processes over the Adriatic are additionally illustrated by the vertical cross--section at Dubrovnik that results from the numerical simulation starting from 00 UTC, 22 April. The cold air outbreak of 20 April did not influence the southern Adriatic region noticeably. Temperature dropped only after midnight on 22 April, when the cold front associated to the cyclone in the Adriatic passed over (Fig. 11a). Wind weakened following the movement of the cyclone from the Adriatic. A temperature fall can be noticed throughout the troposphere. The combined cross-section of potential temperature and equipotential temperature shows that the atmosphere over the southern Adriatic was exceptionally baroclinic, with the upper-level baroclinic zone extending up to 8 km in height. Intresting feature in this figure is a region of oscillations betwen 4 and 8 km on 22 April, probably related to the intense buoyaniy-inertia wave activity. There was no precipitation in the southern Adriatic on 21 April (as seen in figure 6), and the content of humidity started to increase a day later (Fig. 11a). The isolines of equipotential temperature steeply lift up, indicating exceptionally unstable atmosphere. As the cyclonic system moved from the Adriatic to the east by the end of 22 April, the humidity content suddenly decreased and the stability of the upper troposphere began increasing. Below, within the lowest few km of the troposphere, an intense cyclonic circulation was still taking place on 23 April, as confirmed by satellite images and the numerical model.

6. DISCUSSION AND CONCLUSIONS

Sudden cold air outbreaks at the beginning of spring are not rare events in Croatia. They are often accompanied by snow and windstorms responsible for serious damages in agriculture and may cause many difficulties to the traffic between continental and coastal Croatia as well as between the islands and the coast. As many indicators show that the trend of such events is positive (or at least the frequency of their registration increases), understanding and the subsequent forecasting of extreme weather events in Croatia becomes an important task.

Cold outbreaks usually come to the Dinaric Alps and the Adriatic region from the northwest. Arrival of cold fronts and tropospheric troughs over the Alps are frequently accompanied by lee cyclogeneses that later on, depending on the macroscale situation, may further deepen thanks to the diabatic processes over the warmer (relative to the surrounding land) sea. In the weather situation on 20–24 April, the development of a deep cyclone started in the Atlantic and the cyclone later moved from the western Mediterranean to Italy. At the same time an outbreak of cold air over central Europe and the Adriatic significantly contributed to the baroclinicity of the atmosphere. In the lee of the Alps, the cyclone further deepened up to 985 hPa whereas at the same time a secondary cyclone developed in the Adriatic. Mesoscale structures in the Adriatic, not detectable using large-scale analyses alone, have been diagnosed with the aid of satellite imagery and a high-resolution numerical model. An analysis of surface data has shown that the frontal system from the north slowed down over the Dinaric Alps and mid-Adriatic. The two frontal systems merged over the Adriatic on 22 April and the cyclone started to fill up.

The analysis shown in this paper illustrates how macroscale processes, modified over the Dinaric Alps and the Adriatic sea, manifest themselves locally along the Croatian coast. The factor with a dominant influence on the various mesoscale characteristics of the weather in the continental part of Croatia and Dalmatia, is the orographic barrier in between, as previously shown by the numerical studies with and without the Dinaric Alps (Brzović, 1999). The Dinaric Alps channel, at least partially, the propagation of cold fronts further to the east as already described in several previous studies.

An objective analysis of the rawinsonde data at available locations revealed the characteristics of the tropospheric wind field in accordance with previous studies. These confirm the ability of the mesoscale ALADIN/LACE model to reproduce the intensity and time changes of local winds. The model successfully simulated a mesoscale cyclonic vortex developing in the southern Adriatic on 23 April. The influence of local orography in the model is seen in the surface pressure and wind fields, which appear divided on either side of the Apennine peninsula, a feature known as "twin-cyclones". Successful mesoscale model simulations presented in this paper demonstrate the model's potential to forecast a typical chain of weather events over the Adriatic region 48 hours in advance.

The front of 20 April 1997 is a good candidate for further investigation of frontal behaviour over the Dinaric Alps and the mesoscale phenomena associated with it. Using all available data from the national meteorological network, this paper has provided the first observational and modelling results which can eventually be used for similar future studies. Further investigation by numerical experimentation of idealised and real frontal cases will be necessary to find out the details of frontal dynamics and orographically induced processes over the Adriatic region to generalise the preliminary conclusions drawn here.

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