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METEOROLOGICAL FEATURES OF EXTREME PRECIPITATION IN THE NORTHERN ADRIATIC

Meteorološki čimbenici ekstremnih oborina na sjevernom Jadranu

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Abstract: An investigation of extreme precipitation cases in the northern Adriatic area is discussed in this paper. The criterion chosen for an extreme event recognition is a measured daily precipitation amount exceeding 100 mm day^{-1}. In the 1991–2000 period, 18 extreme precipitation events were observed at six meteorological stations in the northern Adriatic and its hinterland. The analysis shows that heavy precipitation occurs most frequently during the autumn season, although it can develop during the other seasons as well.
The large-scale examination performed indicates that heavy precipitation events in the northern Adriatic typically occur under the influence of a deep upper-level trough over western Europe, associated with a low south of the Alps, as shown by the calculated mean charts. This kind of synoptic structure generates a southerly warm and moist low-level flow over the Adriatic Sea, favouring precipitation formation which, in case of larger-scale conditional and potential instability, can lead to intense precipitation events.
Two cases of particular interest were chosen for the mesoscale analysis. In the first case, on 25 December 2000, intense precipitation was both stratiform and convective, while in the second case, on 16/17 September 2000, it was mainly convective. The case studies show that the specific northern Adriatic orography with steep coastal mountain ridges played a major role both in generating prefrontal orogenic precipitation and in intensifying frontal precipitation. In such an unstably stratified environment, the lifting of moist air over the barrier was accompanied by deep convection development in some places.

Key words: extreme precipitation, meteorological features, northern Adriatic

Sažetak: U ovom radu proučavaju se slučajevi ekstremne oborine na području sjevernog Jadrana. Kao kriterij za ekstremnu oborinsku situaciju uzeta je dnevna količina oborine veća od 100 mm dan^{-1}. U razdoblju 1991.–2000. na šest meteoroloških postaja na sjevernom Jadranu i u njegovom zaleđu izdvojeno je 18 ekstremnih situacija. Analiza pokazuje da su situacije ekstremne oborine najčešće u jesen, premda se mogu dogoditi i u drugo vrijeme.
Proučavanje sinoptičkih situacija pokazuje da se intenzivna oborina na sjevernom Jadranu tipično javlja pod utjecajem duboke visinske doline nad zapadnom Europom i ciklone južno od Alpa. Izračunate srednje karte to jasno pokazuju. U spomenutim sinoptičkim okolnostima na Jadranu se javlja toplo i vlažno strujanje južnih smjerova, koje u slučaju nestabilne stratifikacije na širem području može dovesti do pojave ekstremne oborine.
Dvije posebne ekstremne situacije odabrane su za mezoskalnu analizu. U situaciji 25. prosinca 2000. intenzivna oborina bila je i stratiformnog i konvektivnog porijekla, dok je 16/17. rujna 2000. uglavnom konvektivna. Analiza pokazuje da specifična orografija sjevernog Jadrana sa strmim obalnim planinama ima važnu ulogu u razvoju predfrontalne orografske, ali i u pojačavanju frontalne oborine. Podizanje vlažne zračne mase preko planinske prepreke dovelo je na nekim mjestima do razvoja jakih konvektivnih procesa.

Ključne riječi: ekstremne oborine, meteorološki čimbenici, sjeverni Jadran

1. INTRODUCTION

Short-term heavy precipitation can strongly influence the normal life of people, cause traffic disruption, water supply problems, flash flooding, material damage and, in the worst case, human casualties. Intense precipitation is common on the SE slopes of the Alps. One of the climatic maxima of yearly precipitation (1971–1990) is found in Gorski kotar, Croatia, close to the northern Adriatic, as shown by Frei and Schär (1998).

Investigations of heavy precipitation events over the southern (Buzzi and Foschini, 2000) and south-eastern Alps (Vrhovec et al., 2001) have shown that several large-scale and mesoscale features are important for the occurrence of an extreme precipitation event. Those are: 1. a deep upper-level trough extending southwards from Scandinavia to the Mediterranean, often followed by a cyclone development in the Mediterranean (near Genoa), 2. a low-level southerly air flow over the Mediterranean and a pre-frontal, very moist, south-easterly flow located over the Adriatic, 3. the steep mountain ridges of the south-eastern Alps and the Dinaric Mountains responsible for conditional instability release.

An occasional mesoscale cyclonic vortex formed in the northern Adriatic (Ivančan-Picek and Tutiš, 1996) can also be of great importance because of its possible influence on rainfall amount and intensity.

This paper explores extreme precipitation cases in the northern Adriatic area. A case is considered extreme when there is over 100 mm day^{-1} of measured precipitation, affecting both society and the economy. Estimations based on long-time series of annual precipitation maxima have shown that, at the northern Adriatic weather stations, the return period for the occurrence of an extreme daily rainfall amount exceeding 100 mm day^{-1} is about 10 years or more (Gajić-Čapka and Čapka, 1997). According to these estimations, among the 18 observed precipitation events, 11 can be expected to occur even more frequently than once in 10 years, meaning that, statistically, they are not rare events. Six precipitation cases can be considered to be rare events with a return period greater than 10–20 years. One case belongs to the rather rare phenomenon of return period T>50 years.

The goal of this paper is to present the meteorological features and causes of extreme precipitation in the northern Adriatic. The focus is on the investigation of the large-scale forcing and the mesoscale structure, i.e. the ingredients (Doswell III et al., 1996) of heavy precipitation.

During the 10-year period (1991–2000), 18 extreme precipitation events exceeding 100 mm day^{-1} were observed at the six available meteorological stations in the northern Adriatic. On two occasions, over 200 mm day^{-1} were recorded.

Two specific cases have been chosen for a detailed analysis intended to reveal the large-scale and mesoscale weather features likely to be responsible for the extremity of the 24-hour rainfall. A large-scale analysis of synoptic systems was made using model data from the European Centre for Medium-Range Weather Forecasts (hereinafter ECMWF), while the mesoscale analysis was based on the ALADIN (Aire Limitee Adaptation Dynamique development InterNational) forecast model and on HRID (High Resolution Isentropic Diagnosis). The capability of the ALADIN model to predict heavy precipitation events over the eastern side of the Alps during MAP (Mesoscale Alpine Program) was verified by comparing the HRID vertical time cross-sections based on radio-sounding measurements and the ALADIN/LACE prognostic Temps (Ivančan-Picek et al., 2003). Therefore, the present study is concerned mainly with the analysis of meteorological fields rather than with the evaluation of model performances.

The paper is organized as follows. Section 2 contains a description of the data and methods used for diagnosing events. Section 3 presents the large-scale features responsible for the appearance of extreme precipitation on the northern Adriatic area. Two cases are discussed in section 4, the intent being to emphasize the mesoscale features and the differences from average large-scale characteristics. Section 5 concludes the paper.

2. DATA AND ANALYSIS METHODS

The data used in this analysis of extreme precipitation in the northern Adriatic are:

a) climatological data from six meteorological stations in the northern Adriatic and its hinterland (Gospić, Mali Lošinj, Parg, Rijeka, Senj and Zavižan),

b) hourly time series of air pressure, air temperature, relative humidity and precipitation amount,
c) analysis data from the ECMWF,
d) ALADIN/HRv8 operational model data, as well as vertical time cross-sections produced by HRID.

The climatological data consist of a 10-year (1991–2000) daily precipitation amount time series. The ECMWF analysis data of geopotential height, temperature, wind and relative humidity have been provided for 00 UTC, at standard pressure levels (1000 and 500 hPa). The horizontal model resolution is a 1° latitude-longitude grid covering the area of Europe (35°N–70°N and 15°W–30°E). ALADIN hydrostatic limited-area model simulation results have been used for analysing the mesostructure of the total precipitation amount, surface wind and CAPE (Convective Available Potential Energy). A domain of integration covers the area around Croatia (42°N–47°N and 13°E–20°E). The horizontal conformal Lambert grid has a grid size of 8 km. Interpretation of the HRID vertical time cross-sections is based on the physical properties of a number of thermodynamic and stability parameters in saturated and unsaturated air, which, superimposed, reveal many mesoscale features (frontogenesis, convection, etc.) within large-scale atmospheric systems (Glasnović et al., 1994).

The data series of daily precipitation amounts exceeding 100 mm have been collected for 10 years at the available six stations in the area of interest. In the 10-year period 1991–2000, there were 18 occasions when over 100 mm day^{-1} were recorded (Tab. 1). The most intense daily precipitation event (226.7 mm) was observed at the Parg station on 6 September 1998. The relative monthly frequency of daily precipitation amounts greater than 100 mm in the northern Adriatic is shown in Figure 1. Extreme daily precipitation occurs from August till December and also in May, and is most frequent in September and October with a maximum of 39% in October. As it can be seen, heavy precipitation events tend to be most frequent in autumn because the Adriatic Sea is still quite warm from the summer heating, thereby ensuring low static stability in the overlying moist air, while the onset of autumn increases the chances of strong synoptic forcing. A similar situation can be found in the western Mediterranean during the fall (Doswell III et al., 1998).

The mean geopotential height fields in the European area, estimated on the basis of record-

Table 1. Daily precipitation amount R exceeding 100 mm for the 10-year period 1991–2000 in the northern Adriatic area, 18 dates.

Tablica 1. Dnevna količina oborine R veća od 100 mm, u 10-godišnjem razdoblju 1991.–2000. na sjevernom Jadranu, 18 datuma.

Year	Month	Day	R (mm)	Station
1991	11	20	132.1	Rijeka
1992	10	18	117.9	Parg
1992	10	22	106.9	Zavižan
1993	9	5	106.0	M. Lošinj
1993	9	26	116.4	Zavižan
1993	10	22	121.0	Rijeka
1994	8	26	122.1	Zavižan
1994	10	29	101.5	Parg
1995	5	13	100.8	Rijeka
1995	8	29	131.4	Parg
1995	10	31	126.8	M. Lošinj
1996	9	13	123.1	Senj
1998	9	6	226.7	Parg
1998	9	13	100.5	Gospić
1998	10	19	200.0	Rijeka
2000	9	17	175.2	Senj
2000	10	1	126.1	Rijeka
2000	12	26	155.4	Zavižan

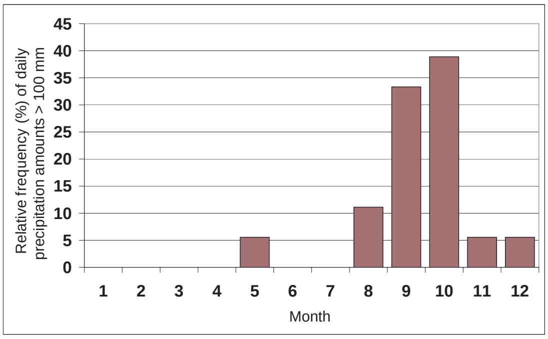


Figure 1. Relative monthly frequency of daily precipitation amounts greater than 100 mm, based on 18 separated dates.

Slika 1. Relativne čestine po mjesecima dnevne količine oborine veće od 100 mm, izračunate na temelju 18 izdvojenih datuma.

ed episodes, are assumed to present a characteristic large-scale weather situation favouring extreme precipitation occurrence. These mean fields (Z_{MEAN}) are calculated using the following expression

$$Z_{\text{MEAN}}(\varphi, \lambda, p) = \frac{1}{18}\sum_{i=1}^{18} Z_i(\varphi, \lambda, p) \qquad (1)$$

where the index i represents the ECMWF geopotential height data for a single precipitation episode (Z_i), ϕ is latitude, λ longitude and p pressure level (1000 or 500 hPa). At every grid point, at a single pressure level, 18 geopotential height values have been averaged in order to estimate the mean value of geopotential height, representing the most common value. An average of 18 geopotential fields provides a useful insight in the general large-scale situation, because the fields are more or less similar. In most cases there is a deep trough or cyclone in the upper levels over western Europe and a low-level cyclone over the western Mediterranean and central Europe.

In addition, two extreme precipitation cases have been selected as primary cases of particular interest. These are:

- 25 December 2000, Zavižan (1594 m a.s.l.), 155.4 mm day^{-1}
- 16/17 September 2000, Senj (26 m a.s.l.), 175.2 mm day^{-1}

These two cases have been chosen for study because they involve diverse characteristics: 1. In both cases, as shown, the 24-hour measured precipitation accumulation exceeds 150 mm, which is comparable with the mean monthly amount, and is of great meteorological and economic importance because of its amount and intensity; 2. There are differences in the spatial and time distribution of precipitation between these two cases; 3. The large-scale weather situation in September shows greater difference than that in December when compared with the average large-scale situation presented as the 18-case average shown in Section 3.

The other reason for choosing these two events was the availability of the ALADIN/HRv8 fields for mesoscale analysis.

3. LARGE-SCALE STRUCTURES

Figure 2 illustrates the mean charts of 500 and 1000 hPa geopotential heights for 18 extreme precipitation episodes over the northern Adriatic during the period 1991–2000, with daily precipitation amounts greater than 100 mm. The mean geopotential height fields for the European area have been calculated on the basis of the ECMWF analysis data as described in Section 2.

Figure 2a shows the 500hPa mean geopotential height, indicating the influence of a deep trough over western and north-western Europe, extending from Scandinavia to the Iberian Peninsula, on heavy precipitation events. The trough axis is tilted in a SW-NE direction causing SW winds over the northern Adriatic. The south-western upper-level flow at the front side of a trough advects warm air throughout the troposphere over the Mediterranean and Adriatic area, while the north-western flow at the rear side of the trough advects colder air over western Europe. This kind of upper-level structure is favourable for maintaining a cyclone over north-western Europe and for starting cyclogenetic processes over the Mediterranean in the lee of the Alps.

The mean charts show that heavy precipitation is mainly associated with a low south of the Alps. A surface low-pressure area, corresponding to a 1000 hPa geopotential height (Fig. 2b), extends to the north, over central Europe. It must be emphasized, that the mean low-level chart shows a well known cut-off process associated with the Alpine lee cyclogenesis connected to a somewhat deeper but more extensive cyclonic field over central and northern Europe. A similar mean pressure

a)

b)

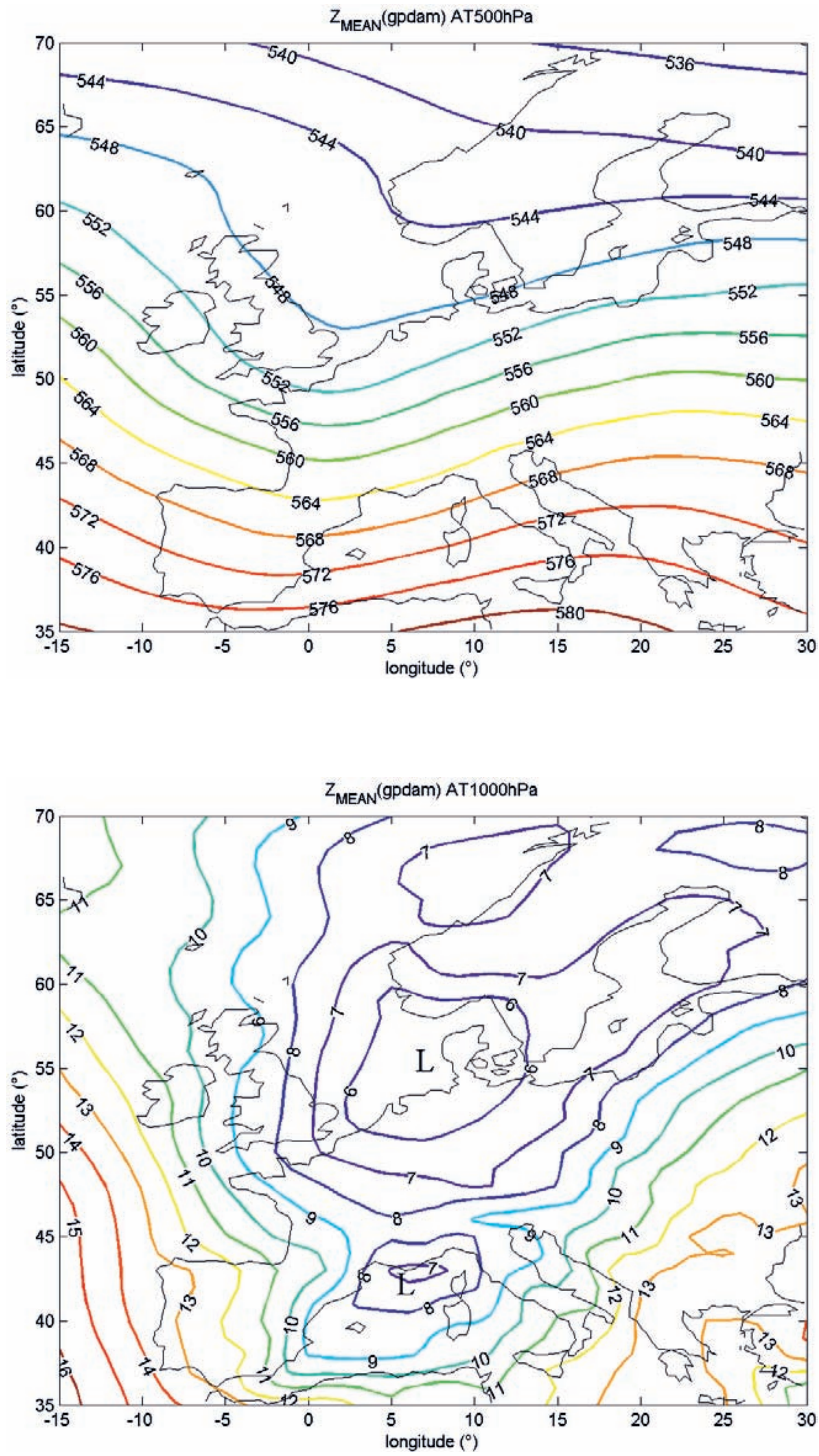


Figure 2. Mean geopotential height fields (Z_{MEAN}) in gpdam: a) at 500 hPa level, every 4 gpdam and b) at 1000 hPa level, every 1 gpdam, according to ECMWF analysis data.

Slika 2. Srednje polje geopotencijalnih visina (Z_{MEAN}) u gpdam na: a) 500 hPa plohi svakih 4 gpdam i b) 1000 hPa plohi svakih 1 gpdam, prema ECMWF analizi.

distribution is characteristic for severe *jugo* wind (Jurčec and Vukičević, 1996). The large-scale cyclonic circulation westward of Croatia causes a rather stationary southerly and south-westerly surface flow over the Mediterranean and the Adriatic Sea. In these synoptic circumstances, prefrontal warm and moist air is advected to the northern Adriatic, almost perpendicular to the steep mountain ridges of the SE Alps and the Dinaric Mountains. The direct orographically forced lifting of warm and moist air initiates thermodynamic processes of cloud and precipitation formation, and can, in case of larger-scale conditional and potential instability, lead to intense precipitation events.

4. CASE STUDIES

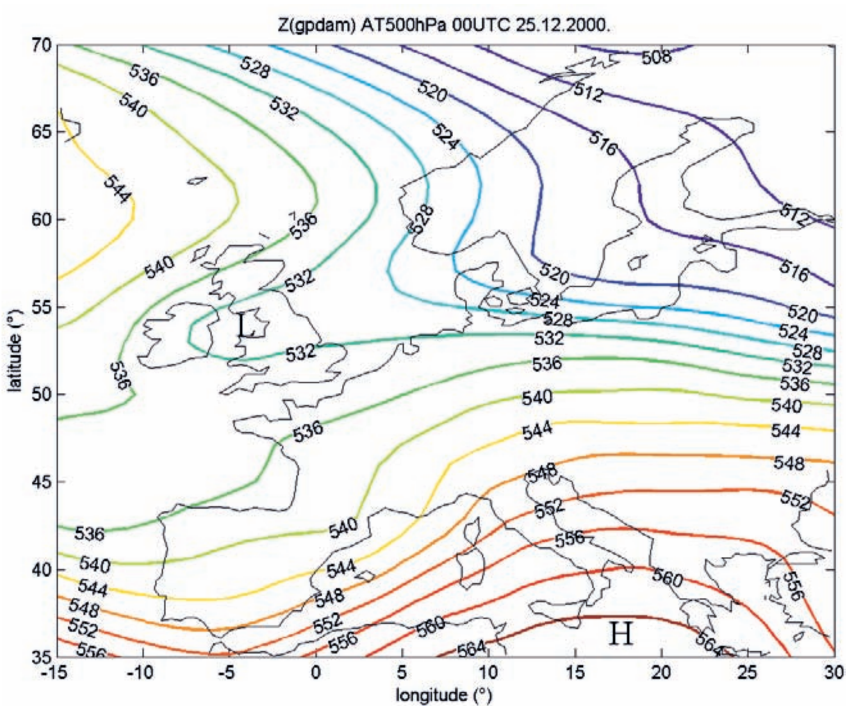
4.1. The case of 25 December 2000

The case was connected to a deep trough that was located over western and north-western Europe on 25 December, 00 UTC, with the axis tilted in a SW-NE direction (Fig. 3a). The upper-level SW winds, at 500 hPa level, were quite strong, as clearly seen from the strong gradients of geopotential, and rather constant over the northern Adriatic area for more than 40 hours. A large surface low-pressure area was formed over the Atlantic, extending over the Gulf of Biskai towards the Mediterranean and central Europe (Fig. 3b). Two low-pressure centres are visible, one over the Atlantic and another over the Gulf of Lyon. The latter was connected to the development of the Mediterranean cyclone slowly moving eastwards to the Gulf of Genoa during 25 December and weakening a bit. An associated warm front passed the Adriatic during the day and was followed by a weak cold front that reached the northern Adriatic later in the night. Over the eastern Mediterranean there was a high-pressure field. In these synoptic circumstances, strong southerly winds, known as *jugo*, were blowing in the area, before and after the warm front passage, advecting warm and moist air throughout the low troposphere. The prefrontal S wind in the warm sector was blocked by the Dinaric barrier and stratiform precipitation was observed over the whole windward coastal side of the mountains. Precipitation was the most intense in the northern Adriatic, particularly in the mountainous region around the Zavižan weather station where an embedded convection developed with thunderstorms and showers. The 24-hour precipitation collected in the form of rain and snow during 25 December in Zavižan was 155.4 mm.

The ALADIN/HRv8 mesoscale model correctly predicted the 24-hour precipitation accumulation around Zavižan and in the hinterland of Rijeka, but to some extent overestimated the amounts that appeared in some areas, particularly on the Istrian Peninsula (Fig. 4a and 4b). When compared to measured data, the 24-hour precipitation forecast underestimated the amounts on the lee side of the coastal mountains. The overall spatial distribution of precipitation in the northern Adriatic area of interest was qualitatively good and accurately predicted.

The HRID vertical time cross-sections (Fig. 5) present the 48-hour ALADIN/HRv8 forecast for Zavižan on 25 and 26 December 2000. It is clearly seen in Figure 5a that during 25 December and in the first few hours of 26 December relative humidity was above 90% in a layer up to 6 km, and, at specific times, up to the height of almost 8 km. High relative humidity and low LCL (Lifting Condensation Level) suggest the presence of a deep stratiform cloud layer during the whole day with embedded thunderstorms after 12 UTC (T-storms were particularly recorded around noon and at night). Besides a deep convection development, convectively unstable areas are also shown in Figure 5b, with partly closed cores of equipotential isotherms in the middle troposphere, while high specific humidity suggests very moist air favourable to intense precipitation. A sudden decrease in relative and specific humidity between 00 and 06 UTC on 26 December shows precipitation weakening after frontal passage. Hourly time series of measured precipitation at Zavižan are not available in winter because of technical reasons, so that temporal changes in precipitation unfortunately can not be verified. However, from observers‘ reports it can be concluded that precipitation lasted the whole day, and was strong by the end of the day. In Figure 5, the time-changes in the vertical distribution of both temperature and equipotential temperature present physical processes connected to the passage of a warm front, in the forenoon of 25 December, and of a cold front in the night to 26 December. The warm frontal zone corresponds to equipotential isentropes in-

a)



b)

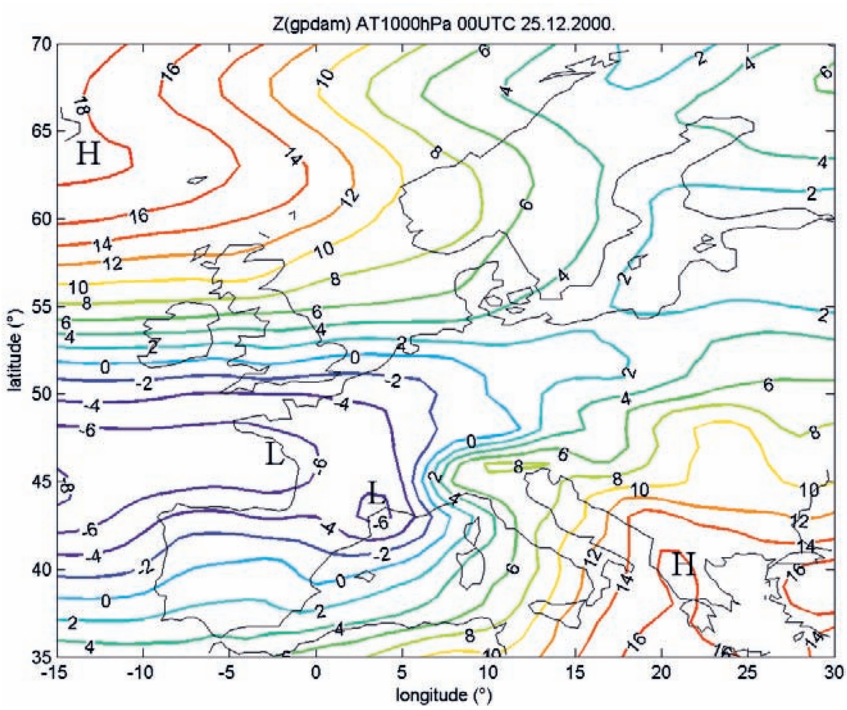


Figure 3. Geopotential height fields in gpdam: a) at 500 hPa level, every 4 gpdam and b) at 1000 hPa level, every 2 gpdam, 25 December 2000, 00 UTC, according to ECMWF analysis.

Slika 3. Geopotencijalne visine izobarnih ploha u gpdam na: a) 500 hPa svakih 4 gpdam i b) 1000 hPa svakih 2 gpdam, 25.12.2000. 00 UTC, prema ECMWF analizi.

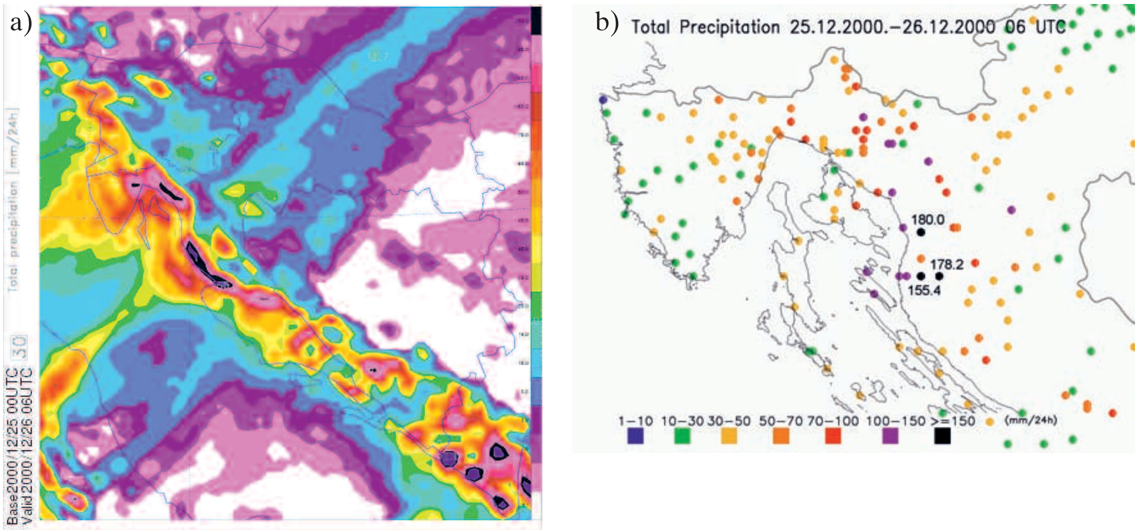


Figure 4. 24-hour total accumulation of precipitation (rain and snow) in mm for the period from 06 UTC on 25 December till 06 UTC on 26 December 2000: a) ALADIN/HRv8 forecast (white: no precipitation, shades of violet and blue: <10 mm, shades of green and yellow: 10–30 mm, every 5 mm, shades of brown and red: 30–80 mm, every 10 mm, pink: 80–100–150 mm and black: 150–200 mm), b) measured precipitation (northern Adriatic).

Slika 4. 24-satna prostorna raspodjela oborine u mm (tekuća i kruta), akumulirane u razdoblju od 06 UTC 25.12. do 06 UTC 26.12.2000.: a) prognoza modela ALADIN/HRv8 (bijelo: nema oborine, nijanse ljubičaste i plave: <10 mm, nijanse zelene i žuto: 10–30 mm uz korak 5 mm, nijanse smeđe i crvene: 30–80 mm uz korak 10 mm, roze: 80–100–150 mm, te crno: 150–200 mm), b) izmjerena oborina (sjeverni Jadran).

clined downward with a simultaneous corresponding temperature increase during warm air advection, while the cold frontal zone is characterised by opposite but more rapid processes. A weak temporal crowding of vertically rising isolines indicates that the cold front was not very strong with regard to the temperature gradient but the flow convergence within the frontal zone very probably helped lifting the prefrontal unstable air and intensified precipitation.

The ALADIN/HRv8 surface charts of the wind field and CAPE at 18 UTC on 25 December and 00 UTC on 26 December 2000 are shown in Figures 6a and 6b. These two charts present the mesoscale weather features which probably contributed to precipitation intensification.

After the warm front passage, accompanied by stratiform precipitation, the northern Adriatic was located in the warm sector of the slowly-moving Genoa cyclone. In those circumstances (Fig. 6a), a strong *jugo* wind was blowing, maintaining a south direction for over 12 hours. The strong flow of warm and moist air from the Adriatic Sea was blocked and lifted by the Dinaric ridges, particularly the Velebit Mountain directed NW-SE. The lifting of moist air led to a conditional instability release and the development of deep convection in the unstable stratified environment, causing intense convective precipitation. This is indicated by high CAPE values, over 1200 Jkg^{-1}, in the vicinity of Zavižan, around 18 UTC and later. Such or higher values of CAPE appear when the weather is very unstable with frequent thunderstorms (Brzović, 1995). Due to the specific topography and canalisation effects of the Rijeka Bay, a small-scale convergence developed, causing an additional increase in vertical velocity and thus intensifying precipitation. At 18 UTC, a weak mesoscale cold front can be seen as a convergence line extending from Istra to Italy. A secondary frontal convergence line was being generated ahead of it, due to wind direction change from south to west under the canalisation and deflection influence of the Apennine orography on somewhat colder eastward-advancing air. In Figures 6a and 6b, these two mesoscale fronts are clearly seen as streaks of

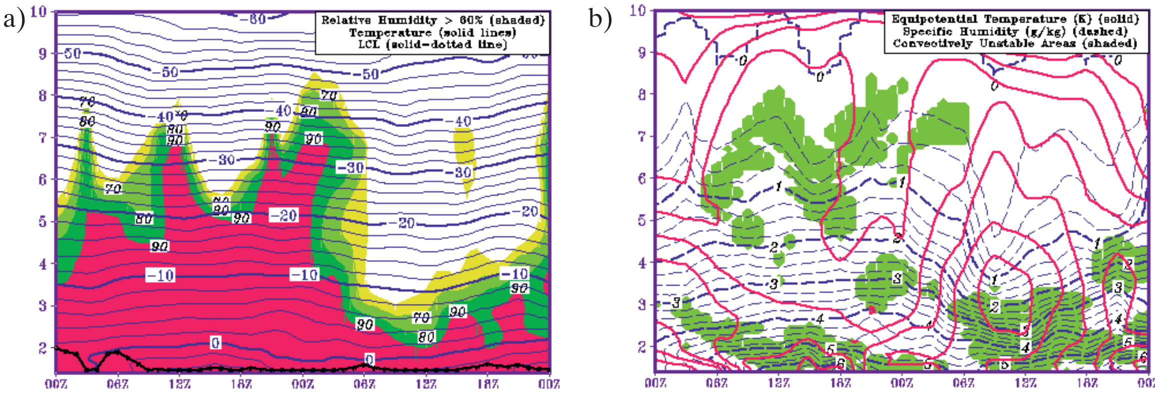


Figure 5. HRID composite vertical time cross-sections: a) temperature (°C, blue solid lines), relative humidity (%, shaded: yellow 60–70%, green 70–90%, red >90%) and LCL height (black dotted line); b) equipotential temperature (K, solid red lines), specific humidity (gkg^{-1}, blue dashed lines) and convectively unstable areas (shaded green) for Zavižan, on 25 and 26 December 2000.

Slika 5. HRID vremenski vertikalni presjeci: a) temperature (°C, plave linije) i relativne vlažnosti (%, žuto: 60–70%, zelene nijanse: 70–90%, crveno: >90%), te visina LCL-a (crna točkasta linija); b) ekvivalentne potencijalne temperature (K, crvene linije) i specifične vlažnosti (gkg^{-1}, plave isprekidane linije), te konvektivno nestabilna područja (zeleno) za Zavižan 25. i 26.12. 2000.

higher CAPE values across the Adriatic and, particularly in the wind field, as distinct convergence lines surrounding divergence area (canalisation effect) at 00 UTC on 26 December (Fig. 6b). The fronts also affected precipitation intensity at Zavižan in the night to 26 December, additionally lifting moist air. After frontal passage the wind was weak and changed to westerly.

4.2. The case of 16/17 September 2000

Compared to the case of 25 December, this case showed both large-scale and mesoscale differences. However, among other similarities, convective precipitation was found in both cases.

The upper-level situation, shown in Figure 7a, was characterized by a deep cyclone over north-western Europe and an upper-level ridge, tilted eastward, over the Mediterranean and central Europe. The westerly winds over the northern Adriatic caused by weak gradients were maintaining direction for over 40 hours and slightly strengthening as the trough was moving eastward. At low levels, at 00 UTC on 16 September (Fig. 7b), a deep eastward-moving cyclone was located over the Northern Sea, extending to central Europe, while a large anticyclone was stationary over eastern Europe. The low-pressure centre weakened slowly as it moved deeper into the continent in the next 24 hours. An associated cold front reached the Alps from NW around noon on 16 September. A typical orographic blocking on the northern slopes of the Alps split the flow of cold air. The flow around the western part of the Alps initiated weak lee cyclogenetic processes, observed in northern Italy in the second part of a day, while the flow around the eastern part was observed as a cold front that reached Croatia from NE, before 00 UTC on 17 September. Most of the time, the northern Adriatic area was located in the non-gradient field with low-surface winds and stable air stratification usual for summer-time weather. However, as a weak cyclone was forming, the weather was gradually changing, instability was increasing and the wind turned to moderate south-westerly, advecting the moist air. The blocking-caused convergence of westerly flow on the windward slopes of the Dinaric mountains was intensified by the cold front lifting, causing precipitation observed in the hinterland of the Kvarner Bay and on the coastal ridges. Particularly, on the Velebit Mountain, a deep moist convection was triggered around Senj just after midnight, when thunderstorms with heavy precipitation (rain showers) were observed. Hourly time series of precipitation amounts (not shown in the paper) show that intense precipitation lasted for about four hours with a peak intensity of over 75 mmh^{-1}, possibly causing increased run-off in the local watershed.

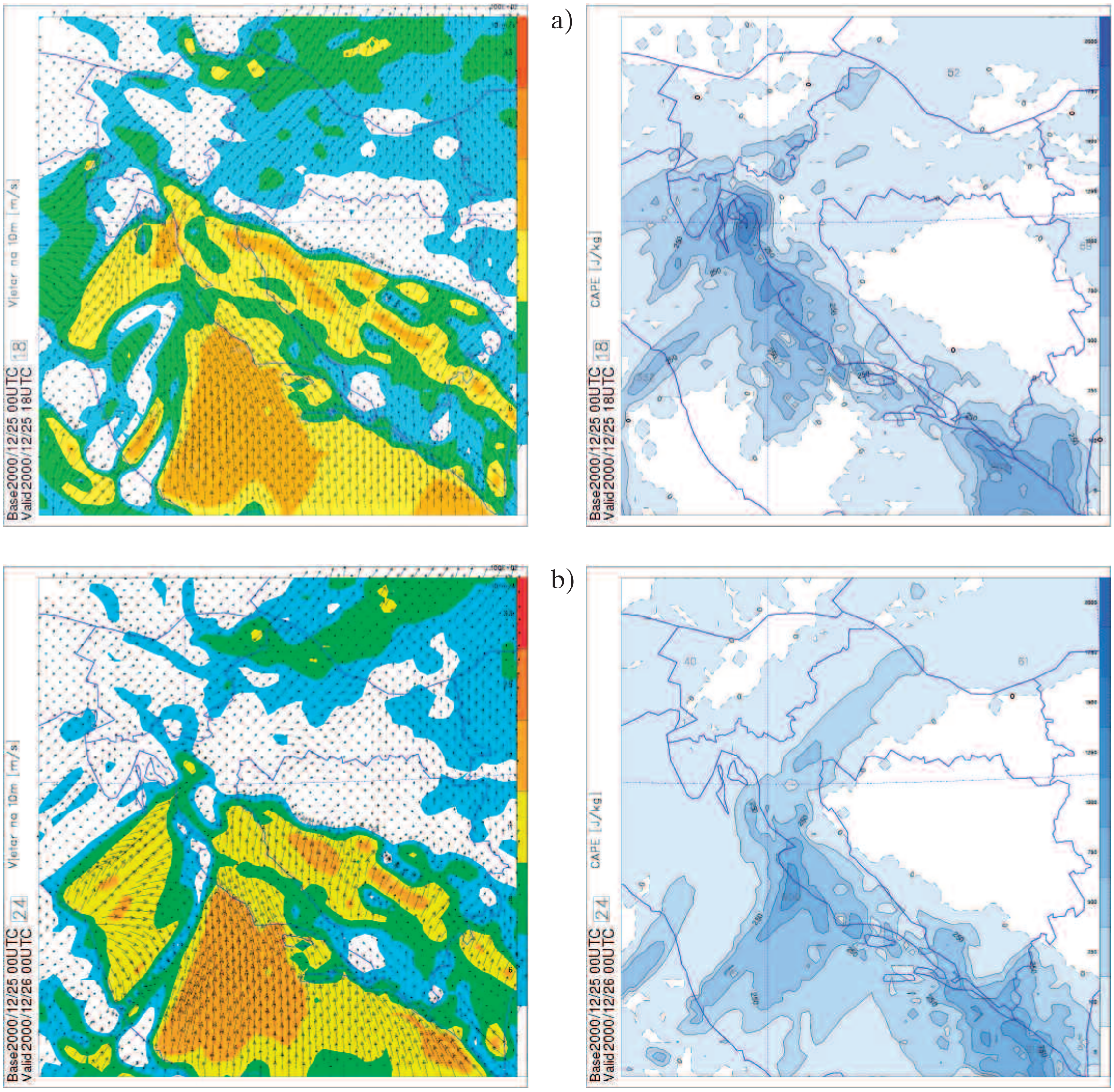


Figure 6. Surface wind fields (ms^{-1}, white: breeze <3.5 ms^{-1}, blue: weak 3.5–5.5 ms^{-1}, green: moderate 5.5–8.0 ms^{-1}, yellow: moderately strong 8.0–10.8 ms^{-1}, light brown: strong 10.8–17.2 ms^{-1}, dark brown: stormy 17.2–24.5 ms^{-1}, red: gale-force >24.5 ms^{-1}) and CAPE (Jkg^{-1}, shades of blue: 0–100–250–2000 Jkg^{-1} at every 250 Jkg^{-1}) at: a) 18 UTC 25 December and b) 00 UTC 26 December 2000, according to the ALADIN/HRv8 forecast.

Slika 6. Prizemna polja vjetra (ms^{-1}, bijelo: povjetarac <3.5 ms^{-1}, plavo: slab 3.5–5.5 ms^{-1}, zeleno: umjeren 5.5–8.0 ms^{-1}, žuto: umjereno jak 8.0–10.8 ms^{-1}, svijetlo smeđe: jak 10.8–17.2 ms^{-1}, tamno smeđe: olujni 17.2–24.5 ms^{-1}, crveno: orkanski >24.5 ms^{-1}) i CAPE-a (Jkg^{-1}, nijanse plave: 0–100–250–2000 Jkg^{-1} uz korak 250 Jkg^{-1}) u terminima: a) 18 UTC 25.12., te b) 00 UTC 26.12.2000., prema prognozi modela ALADIN/HRv8.

The ALADIN/HRv8 mesoscale model prediction results were satisfactory in terms of spatial distribution (Fig. 8a and 8b) and the timing of precipitation. However, the amounts were overestimated in most areas and highly underestimated in the Senj area. Obviously, the ALADIN model, at the considered resolution of 8x8 km, was not capable of accurately reproducing the intensity of the small-scale wet convective processes that occurred around Senj. Generally, it is typical that in situations dominated by deep convection precipitation amounts are systematically underforecast (Romero et al., 2000).

a)

b)

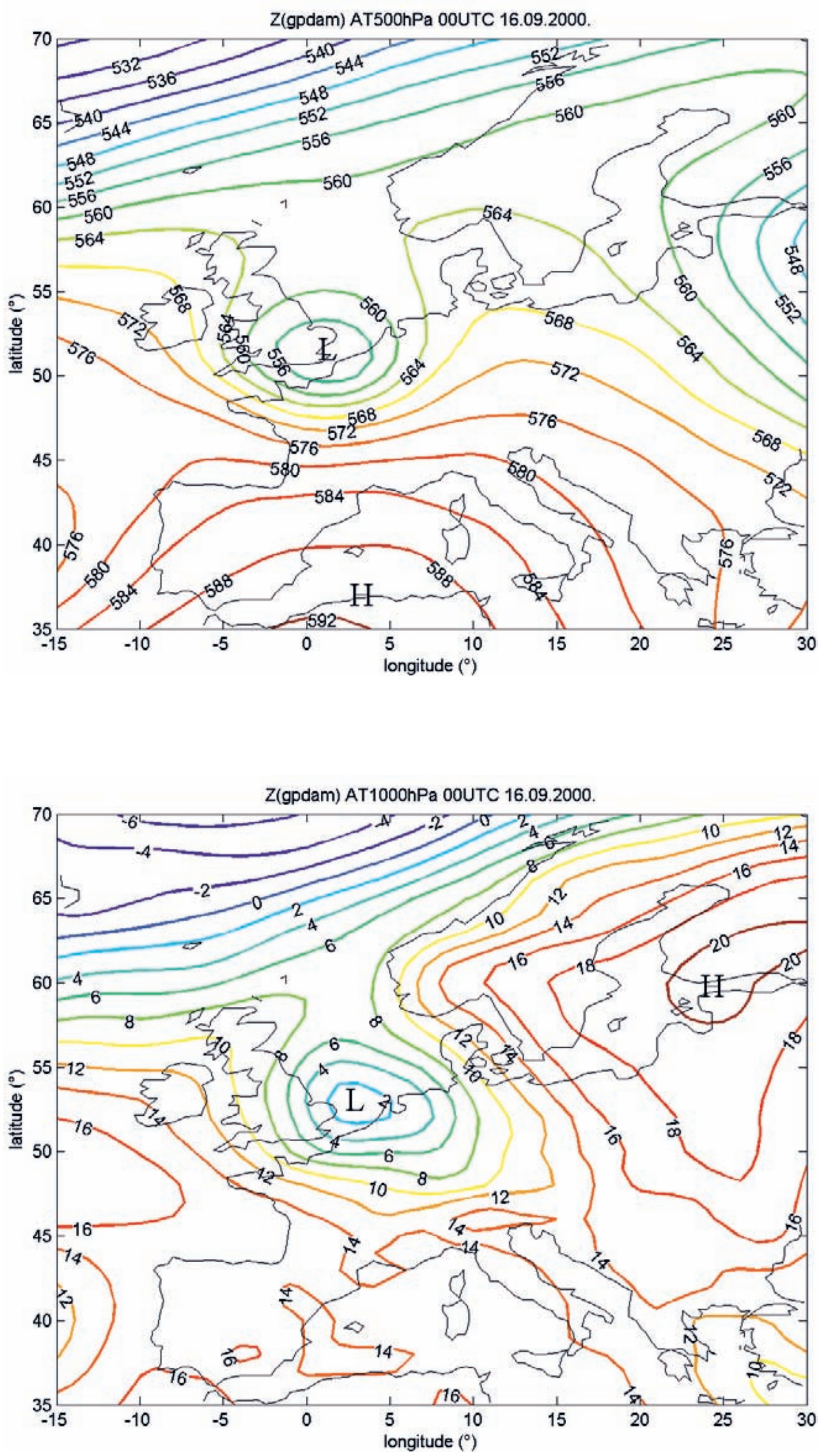


Figure 7. As in Figure 3, only for 16 September 2000, 00 UTC.

Slika 7. Kao i na slici 3, samo za 16.9.2000., 00 UTC.

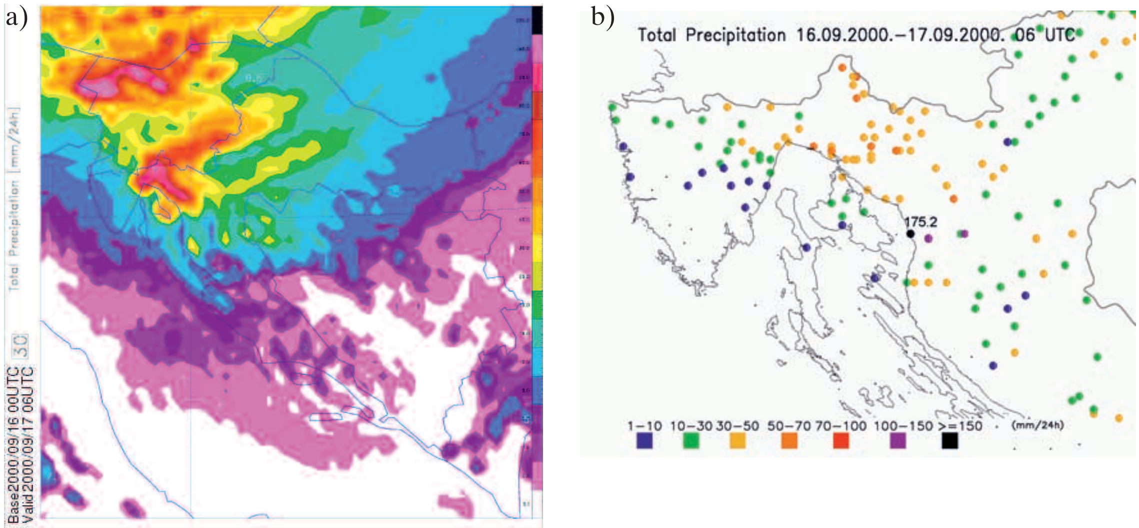


Figure 8. As in Figure 4, only for the period from 06 UTC on 16 September till 06 UTC on 17 September 2000.

Slika 8. Kao i na slici 4, samo za razdoblje od 06 UTC 16.9. do 06 UTC 17.9.2000.

The HRID time vertical cross-sections for Senj on 16 and 17 September are presented in Figure 9. Preceding the time of the largest precipitation, between 00 and 06 UTC on 17 September, somewhat colder air was advected in the upper troposphere (indicated by decreasing isotherms), which additionally labilised the upper-level air mass. In the lower troposphere, an increase in specific humidity indicates moist advection accompanied by unstable stratification shown as closed cores of equipotential isotherms and convective unstable areas. The mesoscale cold front reached the Senj area slightly after 00 UTC on 17 September, which can be concluded from the rapid decrease in temperature and the dense isolines of equipotential temperature in the shallow surface layer. This stable surface layer corresponds to a *bura* wind layer after frontal passage. The lifting of unstable air ahead of the frontal zone formed convective cloudiness and precipitation, seen as an area of high relative humidity above 90%. The ALADIN/HRv8 model predicted convective processes, but they obviously were not predicted strong enough considering the heavy precipitation measured in Senj.

The ALADIN/HRv8 charts (Fig. 10) of the 10-m wind and CAPE at 00 and 06 UTC on 17 September present the surface situation during the period of interest. Several mesoscale weather features are clearly visible, likely to

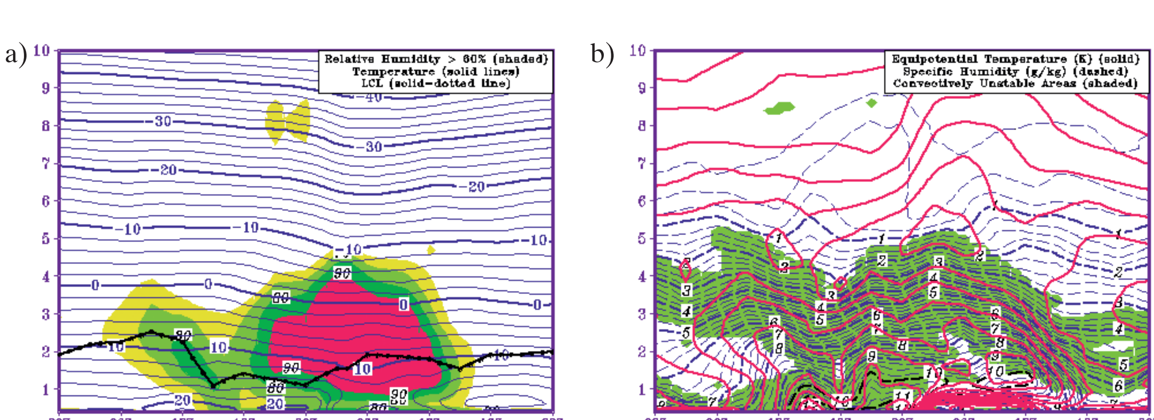


Figure 9. As in Figure 5, only for Senj on 16 and 17 September 2000.

Slika 9. Kao i na slici 5, samo za Senj 16. i 17.9.2000.

influence intense precipitation formation. In Figure 10a, there is a low-level convergence line between westerly and northerly winds located over the mountainous region of Croatia, connected to the aforementioned shallow cold front. In the vicinity of Senj, a strong orographically-induced small-scale convergence is visible. Due to these convergences, a strong convection developed, which is indicated by the CAPE maximum of over 1500 Jkg^{-1} in the Rijeka Bay. After the cold air break to the northern Adriatic Sea, two mesocyclonic vortices were formed due to strong horizontal wind shear. The first one was over the Trieste Bay and the second one over the Kvarner Bay, clearly shown in Figure 10b. The latter was stronger and affected the weather in the Senj area between 00 and 06 UTC. The lifting of moist air, caused by cyclonic low-level convergence within the vortex, very probably intensified the convective precipitation in the area, which is indicated by high CAPE values favourable for thunderstorms.

5. CONCLUSION

On the basis of the extreme precipitation events recorded at the meteorological stations of the northern Adriatic and its hinterland it can be concluded that precipitation amounts exceeding 100 mm day^{-1} are rare phenomena at some stations (the return period is greater than 10 years), but over the whole analysed

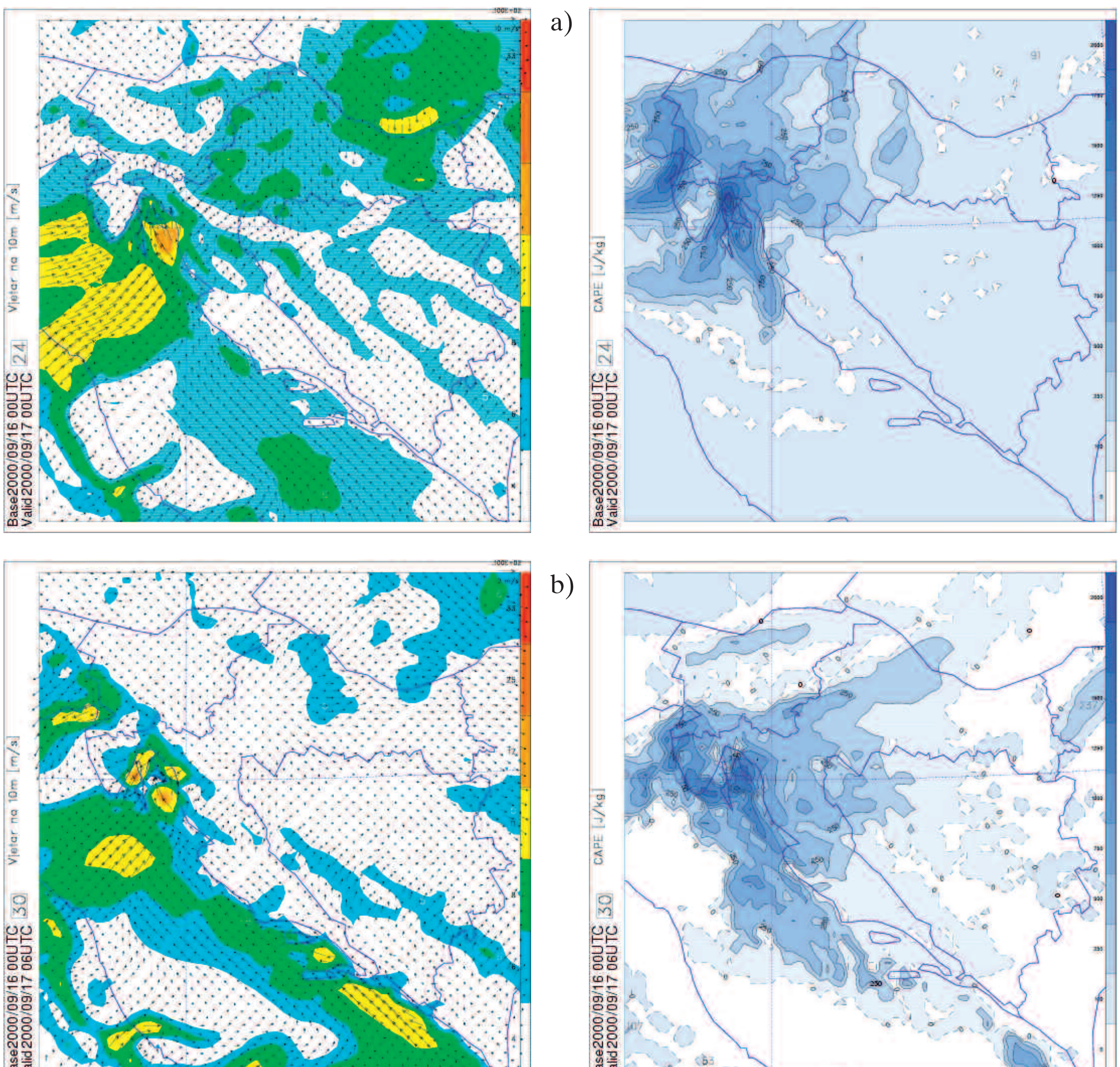


Figure 10. As in Figure 6, only for 17 September 2000 at: a) 00 UTC and b) 06 UTC.

Slika 10. Kao i na slici 6, samo za 17.9.2000. u: a) 00 UTC i b) 06 UTC.

area these amounts are not really statistically rare (on average 2 cases per one year). Furthermore, heavy precipitation events are most frequent in the autumn (September and October), when they are caused by the specific large-scale weather situation and strongly influenced by mesoscale weather features.

The results of the large-scale analysis based on the ECMWF data analysis, show that the responsibility for extreme precipitation occurrence in the northern Adriatic in the period 1991–2000 lies with the Genoa cyclone and the cyclone over central and northern Europe, as well as the upper-level trough over northwestern Europe. It can be concluded that the strength of the Genoa cyclone is not as important as its slow movement through some period of time. These features were presented in the mean geopotential height charts at 500 and 1000 hPa levels.

Case studies, performed using the HRID and ALADIN/HRv8 mesoscale model forecast charts, showed that intense precipitation was formed by the simultaneous influence of several mesoscale features and processes. The frontal influence on extreme precipitation amounts was indicated, although the precipitation was not mainly frontogenetic. The case of 25 December indicated both a warm and cold front influence, and in the second case a cold front was present. In both cases prefrontal moist air was advected by south-westerly winds from the sea. Orography seemed to have a dominant effects in starting wet thermodynamic processes, thus enabling prefrontal orogenic precipitation and intensifying frontal precipitation. In a conditionally unstable environment, the direct mesoscale orographical lifting of warm moist air, followed by a convective available potential energy release, led to deep moist convection and thunderstorm development. Orography also produced a small-scale convergence due to canalisation, flow deflection and barrier blocking, which locally increased vertical velocities and intensified precipitation. The mesoscale cold front and cyclonic vortex features observed in the wind field also contributed to precipitation intensity, producing strong local convergence and air lifting.

It is important to emphasize that the ALADIN/HRv8 mesoscale model was capable of predicting these intense precipitation events. Despite the fact that the 24-hour precipitation amounts were generally slightly overestimated (and underestimated in the case of strong local convective processes), the overall spatial distribution and timing of precipitation was predicted rather well.

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