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Severe Snowstorm 15 - 18 May 1991 Associated with a Mesoscale Cyclone Development over the Adriatic

Snježna oluja 15 - 18. svibnja 1991. povezana s razvojem mezoskalne ciklone na Jadranu

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Abstract

The late snowstorm in southwestern Croatia in May 1991 was associated with the Alpine lee cyclogenesis. The synoptic analysis has confirmed the theoretical concept of lee cyclogenesis which emphasise the role of an oreigenic cold air blocking on the windward side of the Alps with a simultaneous displacement of the local maximum of high level potential vorticity. However, it has been found that the basic causes of a high precipitation amount and a very late snowstorm were processes of a subsynoptic scale, not detected in the standard synoptic analysis. We are trying to prove the association of severe storm with the fast development of a mesoscale vortex over the Adriatic.

Key words: cyclogenesis, snowstorm, Adriatic cyclones, potential vorticity

Sažetak

Snježna oluja u svibnju 1991 u jugozapadnoj Hrvatskoj bila je povezana sa zavjetrinskom alpskom ciklogenezom. Teoretska analiza je potvrdila koncept zavjetrinske ciklogeneze koja naglašava ulogu orogenetskog blokiranja hladnog zraka u navjetrini Alpa i simultanog premještanja lokalnog maksimuma potencijalne vrtložnosti u višoj troposferi. Pokazano je, međutim, da glavni uzrok velike količine oborina i kasnog snijega treba tražiti u procesima podsinoptičkih razmjera koji se ne mogu raspoznati u standardnim sinoptičkim analizama. Namjera ovoga rada bila je da pokušamo dokazati povezanost te oluje s procesom ciklogeneze u mezorazmjerima iznad Jadrana.

Ključne riječi: ciklogeneza, snježna oluja, jadranske ciklone, potencijalna vrtložnost

1. Introduction

Many severe storms in the northern Adriatic are associated with mesoscale cyclones which form in the lee of the Alps and, in their later stage, either develop in the same area or move along the Adriatic sea. The process of the lee cyclogenesis taking place in the western Mediterranean is well studied by a synoptic network of stations in which the average spacing of upper-air observations is about 400 km. Theoretical studies and real data analyses, particularly those in the ALPEX period (Buzzi et al. 1987, Bleck and Mattocks, 1984) emphasise the importance of a connection between potential vorticity (hereafter

PV) in the upper part of the atmosphere and a lee cyclogenesis closely related to the cold air outbreak.

Adriatic mesoscale lee cyclones in some cases are observed after this process, but the synoptic analysis presents them as cyclones moving from the Genoa bay toward NE. The ongoing research is aimed at analysing such cases in order to find out whether the Adriatic cyclones associated with a severe snowstorm really move in such a way or whether they form and develop in this area simultaneously with a decaying cyclone in the western Mediterranean.

This paper presents a case study of the lee cyclogenesis on 15 - 18 May 1991. During the strongest cyclonic development on 16 - 17 May a large part of Croatia experienced a great amount of precipitation (Gospić 68 mm, Ogulin 130 mm) and the air mass was so cold that it caused a snowstorm in Lika and Gorski kotar. An amount of 10 cm of snow in Gospić was the latest event of snowfall since the beginning of observations (1872) in this place. The last instance of such late snow in May was registered on 11 May 1949. At the mountain station Zavižan (Velebit) the amount of new snow exceded 50 cm.

In this case study it was possible to document that this severe storm was associated with a subsynoptic scale process in the Adriatic area, which indicates the importance of separating mesoscale processes from the background macroscale environment (Gomis et al. 1990). Similar studies were conducted by Maddox (1980) considering convective systems on meso-alfa scale (250-2500 km) that appeared to modify their near environment, with the conclusion that this type of system should not be treated as a subgrid feature.

2. Data analysis

The problems in analysing the atmospheric state arise from limitations in the availability, accuracy and representativeness of observational data. Since the real atmosphere is a superposition of wave motions over the entire domain, from large scale to microscale, we have tried to identify the atmospheric meso-alfa-scale disturbance on the basis of real time GTS data using simple interpolation schemes.

The basic data are the original non--uniformly distributed, radiosonde and surface observations. Data are interpolated into a two-dimensional Cartesian grid using an univariate statistical numerical analysis produced by the simplest form of a low-pass objective analysis scheme where the influence of surrounding measurements decreases with inverse distance squared:

$$f(i,j) = \frac{\sum_{n=1}^{N} w_n \, f_n\,(x,y)}{\sum_{n=1}^{N} w_n}$$

$$w_n = d_n^{-2}$$

where $f_n\,(x,y)$ represents the observed data, $f\,(i,j)$ are grid point data, w_n is the weight function, and d_n is the distance from the grid point to the observed data. If the weighting function reaches infinity, then the grid value equals the closest data point.

The horizontal spacing is 50° km at 45° latitude on a polar-stereographic projection, so that horizontal motions smaller than 150 km are smoothed out.

Upper level analyses are available at standard pressure levels at 00 UTC and 12 UTC. In the present analysis the midnight data are used when the radiosounding data from Zadar are available. Surface analyses are performed four times per day (00, 06, 12 and 18 UTC).

The analysed variables at pressure levels are: geopotential height, temperature, horizontal wind components and relative (or specific) humidity. Diagnostic relations between meteorological parameters provide the means for extracting new fields from the analysed variables. It is important to notice that diagnostic studies of the atmosphere may exploit different "best analyses" from the" best analyses" used in the initialization of a numerical forecast.

The study has been performed using the following assumptions:

1) meso - α scale atmospheric disturbances destroy the geostrophic balance on macro and

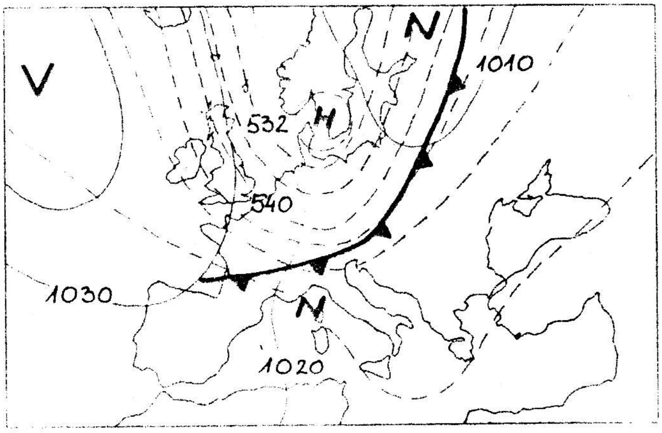


Fig.1.a Surface pressure and RT 500/1000 on 15 May 1991 at 00 UTC
Sl.1.a Prizemno polje tlaka i RT 500/1000 15.05.1991 u 00 UTC

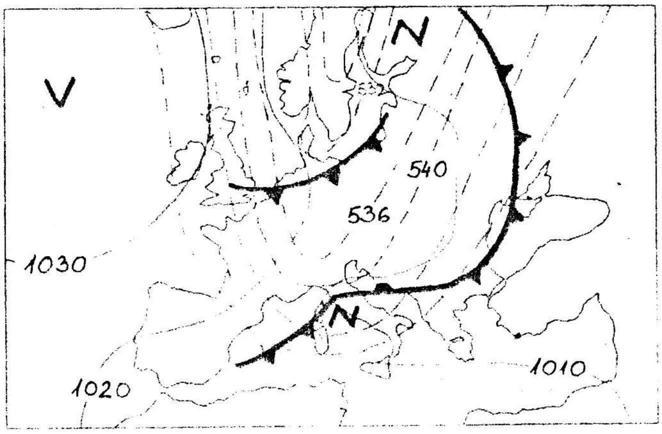


Fig.1.b Surface pressure and RT 500/1000 on 16 May 1991 at 00 UTC
Sl.1.b Prizemno polje tlaka i RT 500/1000 16.05.1991 u 00 UTC

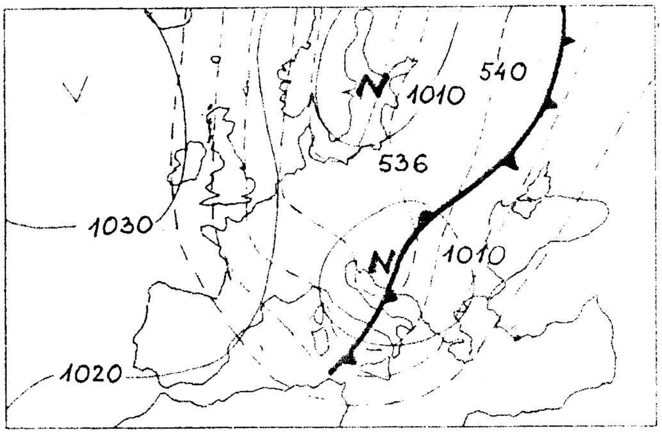


Fig.1.c Surface pressure and RT 500/1000 on 17 May 1991 at 00 UTC
Sl.1.c Prizemno polje tlaka i RT 500/1000 17.05.1991 u 00 UTC

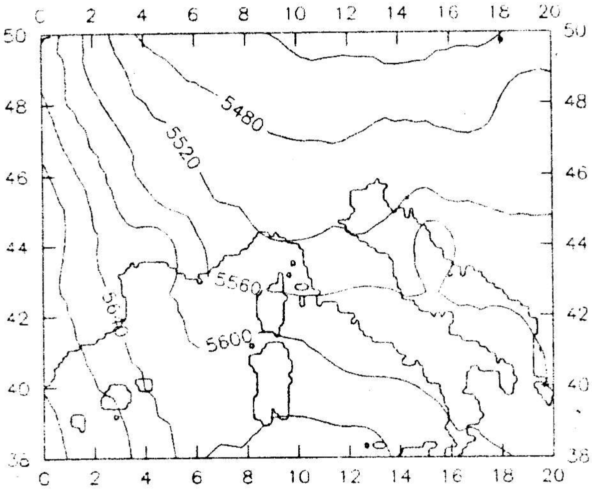


Fig.1.d AT 500 hPa on 16 May 1991 at 00 UTC
Sl.1.d AT 500 hPa, 16.05.1991. u 00 UTC

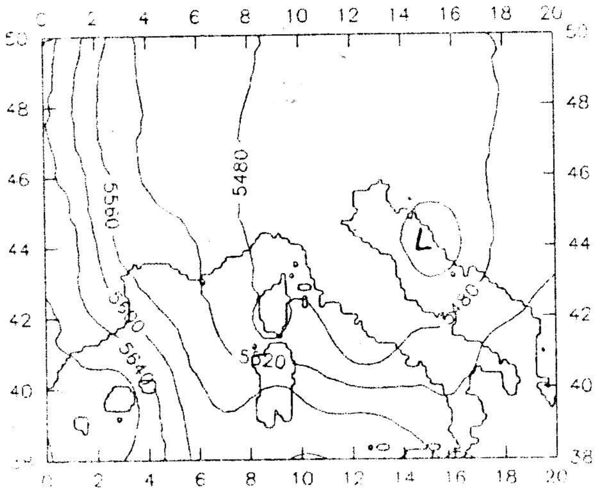


Fig.1.e AT 500 hPa on 17 May 1991 at 00 UTC
Sl.1.e AT 500 hPa, 17.05.1991. u 00 UTC

meso - α scale

2) baroclinicity is the most important atmospheric property during the cyclogenetic process

3) data quality is subjectively controlled and manually corrected where necessary,

4) the signal of ageostrophic motion is included in the original data set.

3. Synoptic analysis 15 - 18 May 1991

The main large-scale, low-level pressure centers at the beginning of this development were a High over the Atlantic, northwest of England and a Low over Scandinavia, a usual "parent" cyclone in the Alpine cyclogenesis (Fig.1.a,b), accompanied by a meridionally elongated deep trough of a Rossby wave at higher levels with the axis over the central Europe. Such tropospheric stratification introduced a very strong surface pressure gradient in the W-E direction, over central Europe. Moreover, a frontal deformation took place over the Alps, and a shallow depression formed in the Genoa bay.

The thickness chart 500/1000 indicates that a very cold air mass was progressing at the rear of the front in a strong current toward the Alps. 24 hours later (Fig. 1.c) the front was moving across the Alps with the simultaneous deepening of a lee depression and cyclone formation in the Genoa bay. A further cold air invasion, with a cold surge from the north entered the European continent causing intensification of the high pressure field over central Europe.

Cold air entered the Mediterranean through the "Vienna channel" across the Dinaric Alps. This process caused a deepening and further development of a cyclone which was now more pronounced at higher levels (Figs 1.d and 1.e). That process was simultaneously followed by stormy weather in most part of Croatia.

The analysis of this case study indicates that the entire process of lee cyclogenesis takes place in an already baroclinically unstable area, rich with moisture. At the full stage of the development of the main lee cyclone in the western Mediteranean, over the northern Adriatic there was a convergence of surface air currents with local convective instability (Fig.3.a)

The greatest advantage in the present case study was the availability of radiosoundings in Zadar at two important moments. One sounding preceeded the cyclone formation, and the second sounding, 24 hours later, was carried through the center of the cyclone moving to the northeast.

4. Thermodynamic characteristics of the developing mesoscale cyclone

The concept in which a surface orographic blocking of cold air and a simultaneous sinking of upper tropospheric and stratospheric dry air of high potential vorticity are related to the cyclogenesis process has been considered from a theoretical point of view.

In this case of cyclogenesis there are pronounced diabatic effects due to heat released during the precipitation process in a very humid air.

Figs 2. a,b,c,d,e,f,g,h and i show the distribution of the surface pressure field every 6 hours on 16 and 17 May 1991 according to original GTS data. Generally, all the figures show higher pressure NW of Italy and lower pressure in the central Mediterranean. The meso- α surface pressure analysis on 16 May 1991 at 00 UTC does not show closed isobars in the Genoa gulf, as indicated in the large-scale analysis, but rather only a trough of the main broad low centre placed in the central Mediterranean. Fig. 2b, describing the surface pressure field 6 hours later, shows closed isobars around central Italy. At 18 UTC this very well defined low pressure centre deepened further in the mid-Adriatic area, while on 17 May 1991 at 00 UTC the centre of the cyclone was on the nothern part of the mid-Adriatic, now embedding the Zadar area. It is important to notice the indicated double-low structure of the centre of the cyclone (which again appears in Fig. 2.e) - one mesoscale closed low is upstream and another one is situated downstream of the orographic barrier.

Figs 3.a,b and c show the surface wind fields on 16 May at 12 UTC and 17 May at 00 and 12 UTC. On Fig.3.a there is a region of weak northeasterly winds in the western part of the Panonian valley and simultaneously, there are regions of stronger southerly flow in the Mediterranean (particularly a southwesterly flow over Tirrenian sea and southeasterly Scirocco over the most of the Adriatic sea). Twelve hours later, the whole eastern area of the Adriatic and the coastal part of the Balcan Peninsula exibit weak westerly and southwesterly winds (Fig. 3.b), a situation favourable for inhancing precipitation due to orography. On 17 May at 12 UTC (Figs 3.c) the strongest stage of the cyclone was over, so that westerly winds prevailed over the whole area under consideration although there were areas of local convergence or divergence.

Figs 4.a,b and c show observed surface winds over Croatia on the basis of all available synoptic and climatological data.

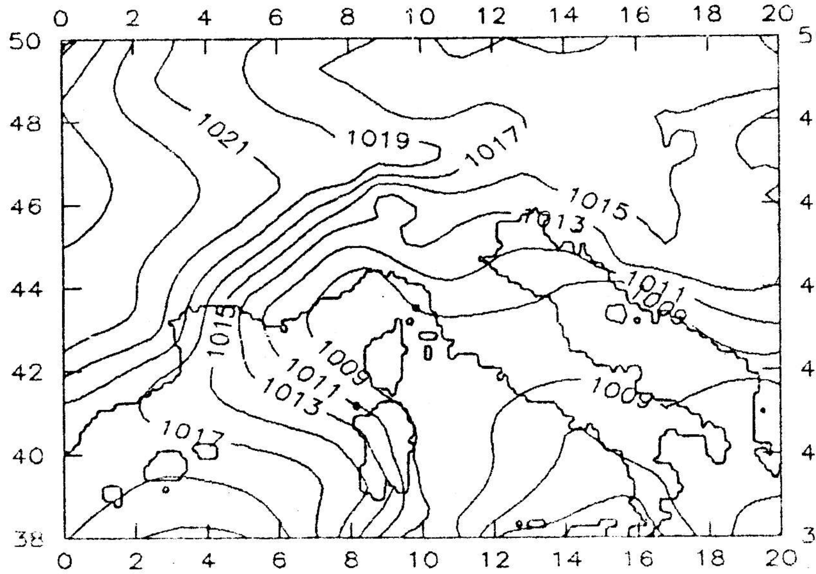


Fig.2.a Surface pressure on 16 May 1991 at 00 UTC (axes - degrees of geog. latitude and longitude)
Sl.2.a Prizemno polje tlaka 16.05.1991. u 00 UTC Na osima su označeni stupnjevi geografske širine i dužine.

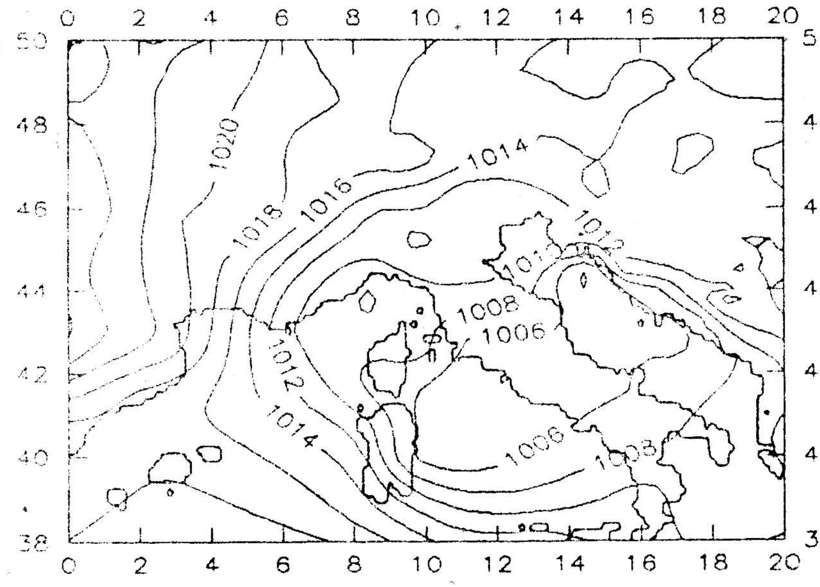


Fig.2.b Surface pressure on 16 May 1991 at 06 UTC Sl.2.b Prizemno polje tlaka 16.05.1991. u 06 UTC

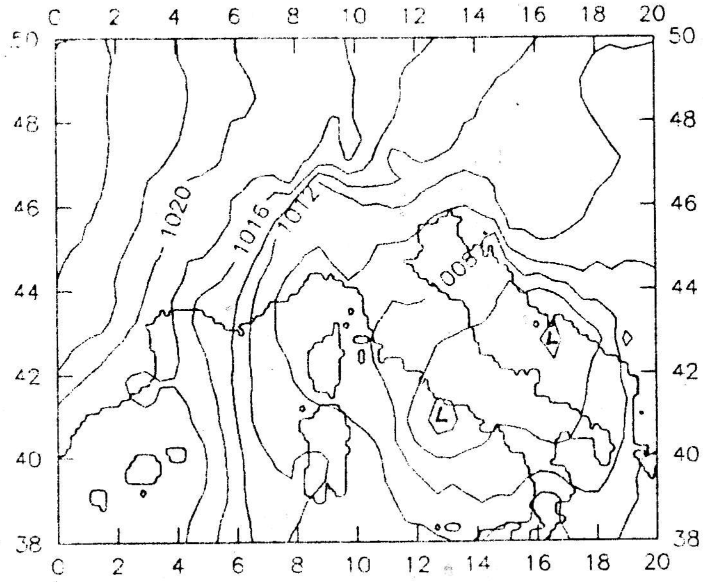


Fig.2.c Surface pressure on 16 May 1991 at 12 UTC Sl.2.c Prizemno polje tlaka 16.05.1991. u 12 UTC

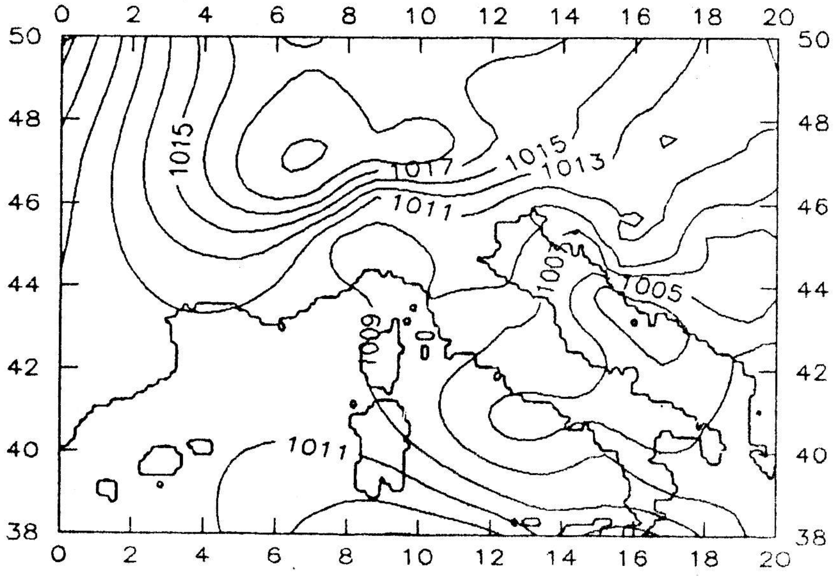


Fig.2.d Surface pressure on 16 May 1991 at 18 UTC   Sl.2.d Prizemno polje tlaka 16.05.1991. u 18 UTC

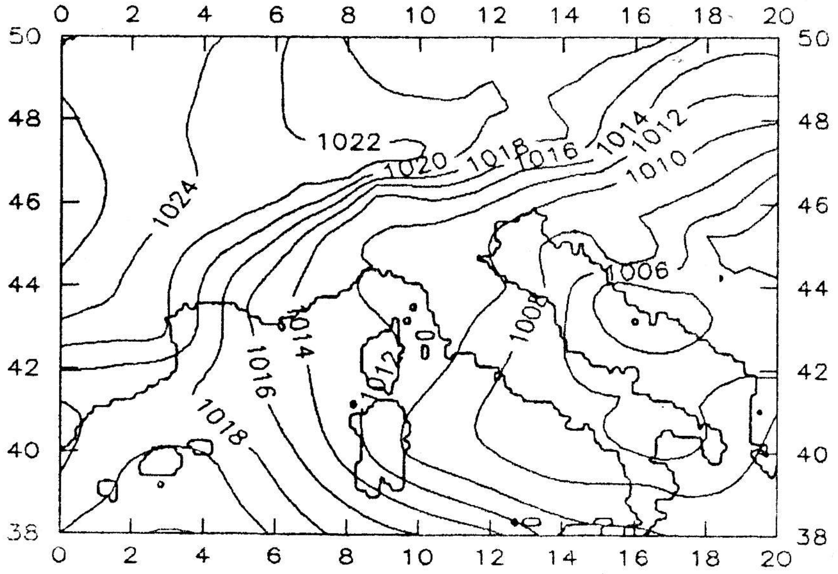


Fig.2.e Surface pressure on 17 May 1991 at 00 UTC   Sl.2.e Prizemno polje tlaka 17.05.1991. u 00 UTC

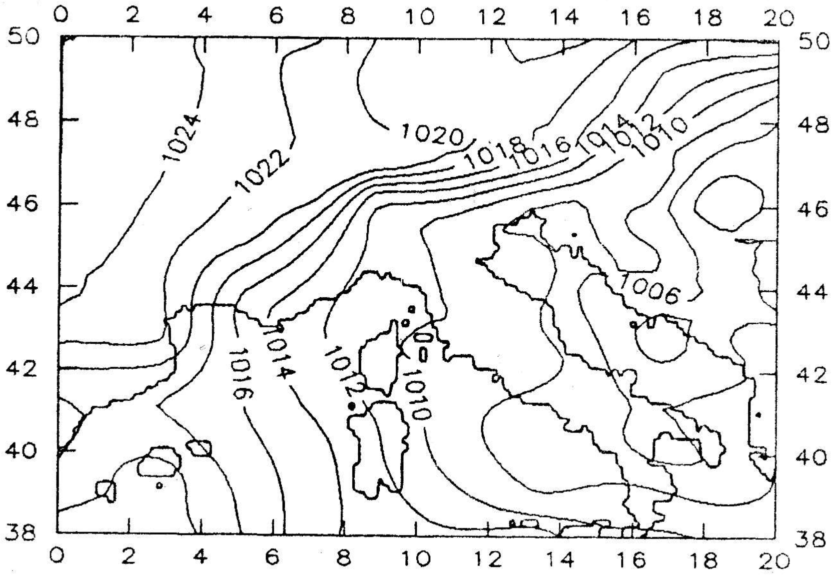


Fig.2.f Surface pressure on 17 May 1991 at 06 UTC   Sl.2.f Prizemno polje tlaka 17.05.1991. u 06 UTC

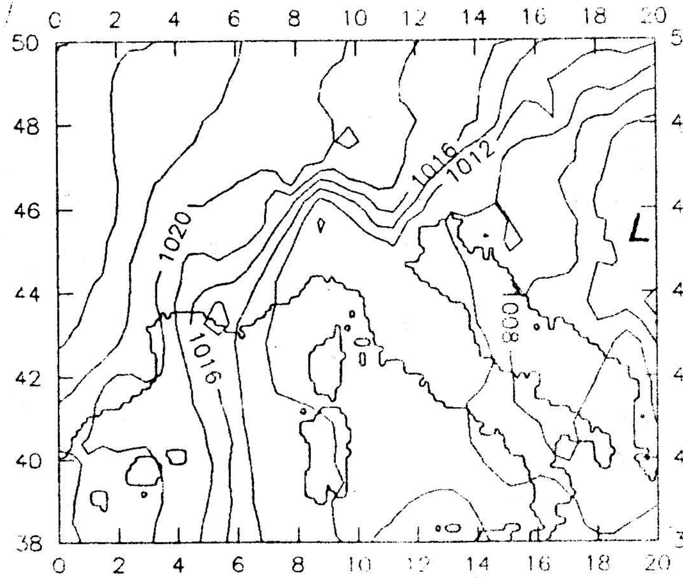


Fig.2.g Surface pressure on 17 May 1991 at 12 UTC

Sl.2.g Prizemno polje tlaka 17.05.1991. u 12 UTC

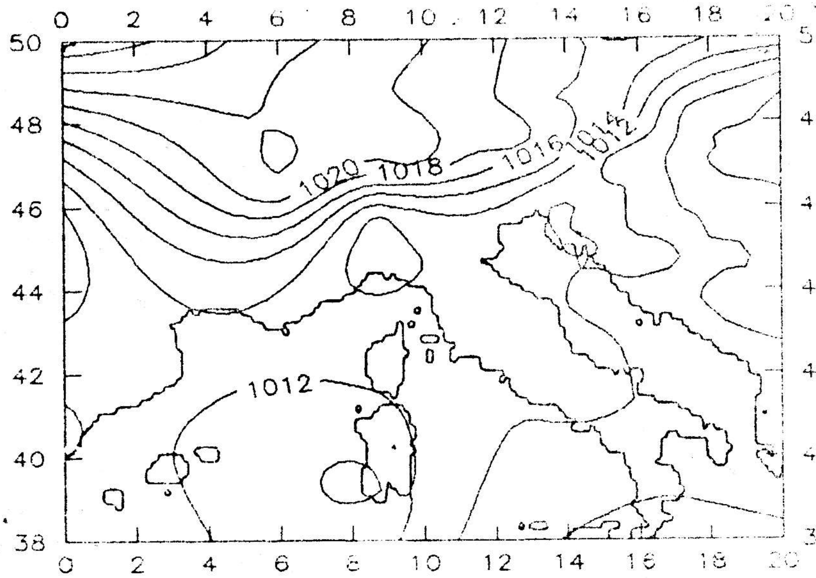


Fig.2.h Surface pressure on 17 May 1991 at 18 UTC

Sl.2.h Prizemno polje tlaka 17.05.1991. u 18 UTC

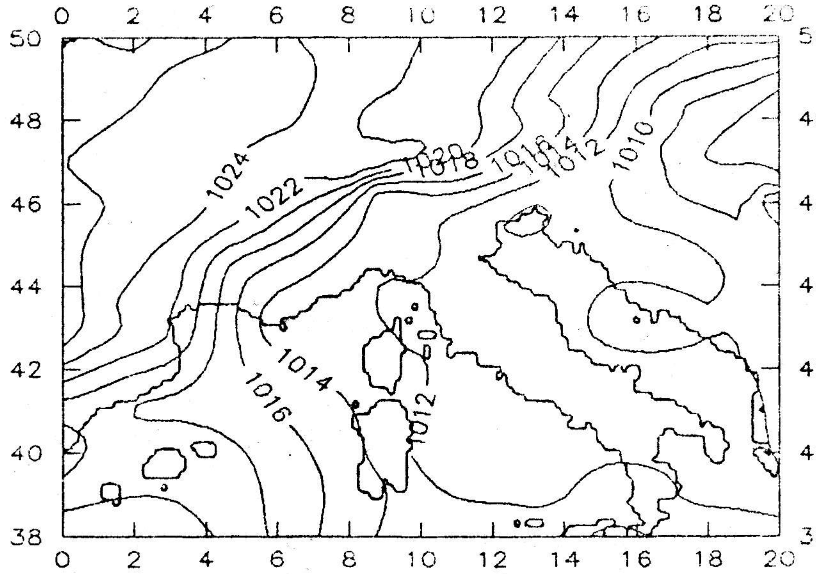


Fig.2.i Surface pressure on 18 May 1991 at 00 UTC

Sl.2.i Prizemno polje tlaka 18.05.1991. u 00 UTC

Fig.3.a Surface wind field on 16 May 1991 at 12 UTC
Sl.3.a Prizemno polje vjetra, 16.05.1991. u 12 UTC

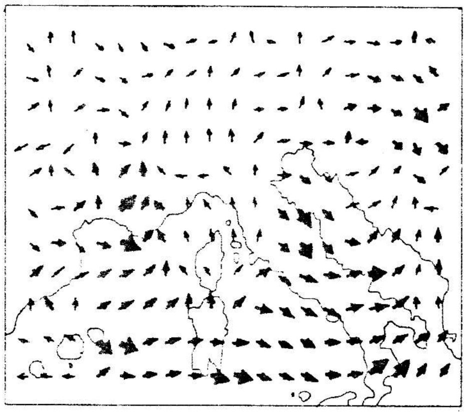


Fig.3.b Surface wind field on 17 May 1991 at 00 UTC
Sl.3.b Prizemno polje vjetra, 17.05.1991. u 00 UTC

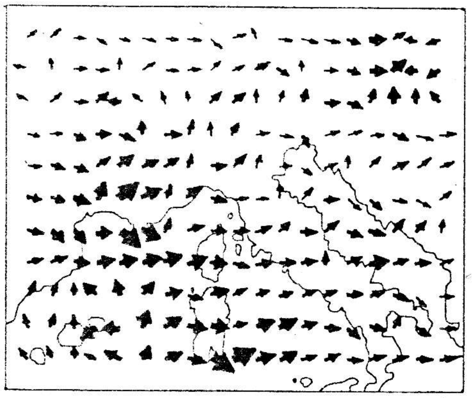


Fig.3.c Surface wind field on 17 May 1991 at 12 UTC
Sl.3.c Prizemno polje vjetra, 17.05.1991. u 12 UTC

Fig.4 Surface wind direction over Croatia on the basis of synoptic and climatological stations
a) 16 May 1991 at 13 UTC
b) 16 May 1991 at 20 UTC
c) 17 May 1991 at 06 UTC
Sl.4 Prizemni smjer vjetra na području Hrvatske iz podataka sinoptičkih i klimatoloških postaja
a) 16.05.1991. u 13 UTC
b) 16.05.1991. u 20 UTC
c) 17.05.1991. u 06 UTC

Analyses of those charts, describing local winds, were the most crucial for defininig the exact front position and its′ movement and deformation. The two main points of the frontal deformation can be located over Croatia - one is over the mid-Adriatic and another over the nort-eastern part of Croatia, stressing the fact that although the general macro-scale location of the atmospheric disturbance to some extent remained unaltered, there were smaller-scale disturbances which, in fact, determined the actual weather.

For better vertical description of the atmosphere, vertical space cross-sections of a wind component parallel with the cross section are shown in Figs 5.a and 5.b. Both figures show a shallow layer of reversed airflow coming from the northeast, mostly below a 3 km height, because the part of the cross-section line is placed in the rear of the front. Montgomery potential is defined by:

$$M = c_p T + gz = \Theta \Pi + \Phi$$

where c_p is specific heat at constant pressure, T the absolute temperature at the height z and g the gravitational constant. The alternative expession involves the absolute potential temperature Θ, the Exner function Π and geopotential Φ. Montgomery potential gives the sum of specific enthalpy and geopotential energy of the system and has a dimension of specific energy. The lowest values of the Montgomery potential therefore coincide with the low energy process (see Fig.6). The simultaneous surface wind field (Fig.3a) over the area of the minimum Montgomery potential is characterised by relatively weak NE winds, indicating a blocking of the airstream on the windward side of the narrowest part of the Dinaric Alps.

One of the thermodynamic mass invariant is the equivalent potential temperature Θ_e which is given for a saturated air particle, by the relation (Bolton, 1980):

$$\Theta_e=\Theta' \exp[(\frac{3.376}{T_k} - 0.00254)\, m\, (1+0.81\ 10^{-3}\, m)]$$

$$\Theta'=T(\frac{1000}{p})^{0.2854(1-0.00028\, m)}$$

where T_k, p, and m are the absolute temperature, pressure and mixing ratio at the initial level and T_L is the absolute temperature at the lifting condensation level, given by:

$$T_L= \frac{2840}{3.5 \ln T_k - \ln e - 4.805} + 55$$

where e is the saturated vapor pressure (mb) of water (the well-known formula of Magnus - Tetens).

Figs 7. a, b and c show the surface distribution of the equipotential temperature Θ_e every 12 hours. Warmer and moist air is in the Mediterranean area while colder and drier air is over the continent. Moreover, there is a constant mesoscale low in the surface field of Θ_e over the narrowest part of the Dinaric Alps (as part of the colder airmass inland) while there are strong gradients in the coastal area.

The vertical cross sections of Θ and Θ_e (Figs.8.a,b,c and d) indicate frontal zones and descending motions in the lowest twelve km of the atmosphere.

Taking into consideration moisture in the atmospheric processes, it is obvious that the slopes of Θ_e isolines in the center of the cyclone are more pronounced than the ones in the cross section of the dry adiabatic isentropic surfaces.

A study of the advection of relative vorticity, as one of the elements of local vorticity changes, shows (Fig. 9) that the vorticity advection was pronounced only on 16 May, 00 UTC. This resulted in a strong positive change over the north Adriatic and a weaker negative change over the mid-Adriatic.

After 24 hours there was no essential contribution of the advective term to the local change of relative vorticity. According to observations (Fig.10), the significant local change of relative vorticity on 16 May at 00 UTC just preceded the period of most intense precipitation.

Orographically caused precipitation enhancement is visible in precipitation amounts registered on 16 May at 06 UTC and on 16 May at 18 UTC (although the maximum over Dalmatia is most probably due to the mesoscale vortex itself).

Potential vorticity (PV) could also be considered a conservative air property and

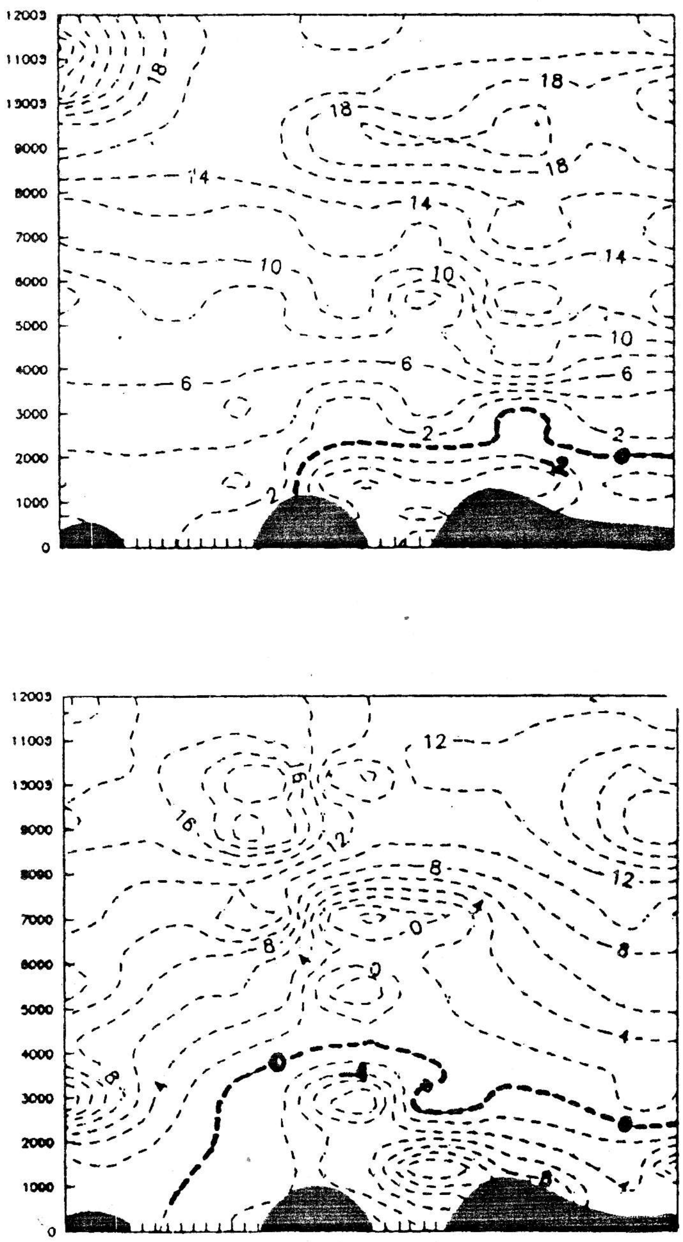


Fig.5 Vertical cross-section of the wind component paralel to the cross-section (the line AB in Fig.9 marks the location of the cross-section)

a) 16 May 1991 at 00 UTC

b) 17 May 1991 at 00 UTC The vertical axis is in metres.

Sl.5 Vertikalni prostorni presjek komponente vjetra paralelne s presjekom (presjek je naznačen na slici 9, linijom AB, koja je približno okomita na Velebit)

a) 16.05.1991. u 00 UTC

b) 17.05.1991. u 00 UTC Visina je označena u metrima.

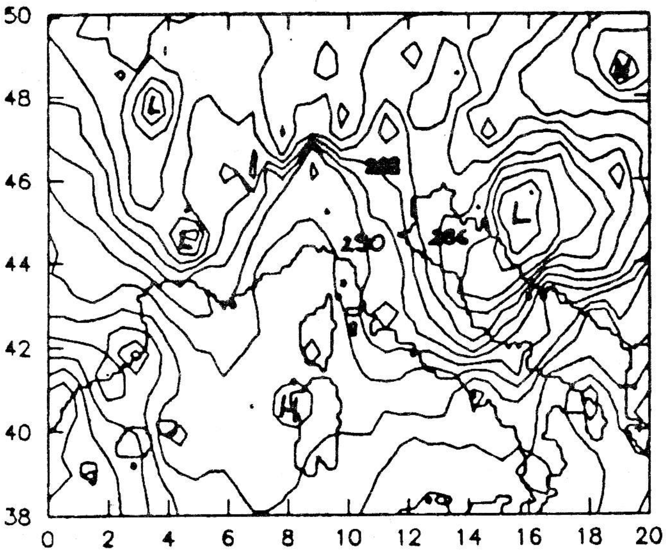


Fig.6 Surface distribution of the Montgomery potential M on 16 May 1991 at 12 UTC (units: 1000 m^2/s^2)

Sl.6 Prizemna raspodjela Montgomery potencijala 16.05.1991. u 12 UTC (jedinice: 1000 m^2/s^2).

could be applied as an indication of the displacement of an air particle of certain thermodynamic characteristics. In this study we consider PV defined as

$$PV = - g\,(f\,\mathbf{k} + \nabla_p * \mathbf{V})\,\nabla_p\Theta$$

(in the isobaric coordinate system) where $\nabla_p x \mathbf{V}$ is the relative vorticity on the isobaric surface, and $\nabla_p\Theta$ represents the static stability and $\mathbf{k}$ is a unit vertical vector.

The PV parameter is useful in the analysis of atmospheric disturbances since it combines the dynamic and thermodynamic parameters - absolute vorticity and static stability (Tafferner, 1990).

Fig.11. shows the consecutive positions of the local PV maxima on 15, 16 and 17 May at 00 UTC, which are displaced from the interior of Croatia to Dalmatia where a mesoscale cyclonic vortex is generated.

In the first phase of the cyclogenesis the maximum of PV follows the airstream across the mountain, whereas the cold air is more or less blocked on the windward side. Such a blocking leads to a hydrostatic pressure rise on the windward side, whereas in the lee, due to the divergence of mass flow in front of the PV maximum, a pressure fall

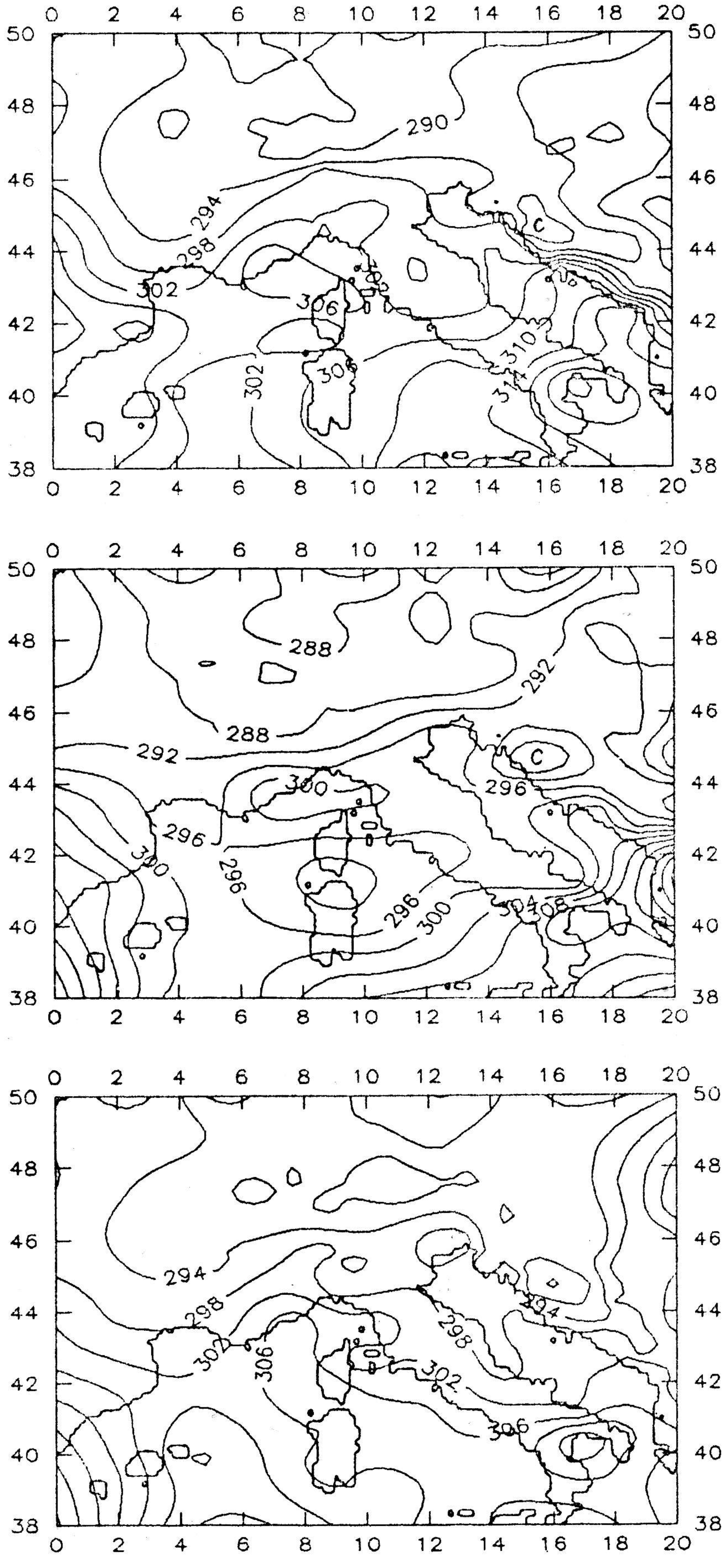


Fig.7 Surface equipotential temperature field
(a) 16 May 1991 at 12 UTC
(b) 17 May 1991 at 00 UTC
(c) 17 May 1991 at 12 UTC

Sl.7 Prizemna raspodjela ekvipotencijalne temperature zraka
(a) 16.05.1991. u 12 UTC
(b) 17.05.1991. u 00 UTC
(c) 17.05.1991. u 12 UTC

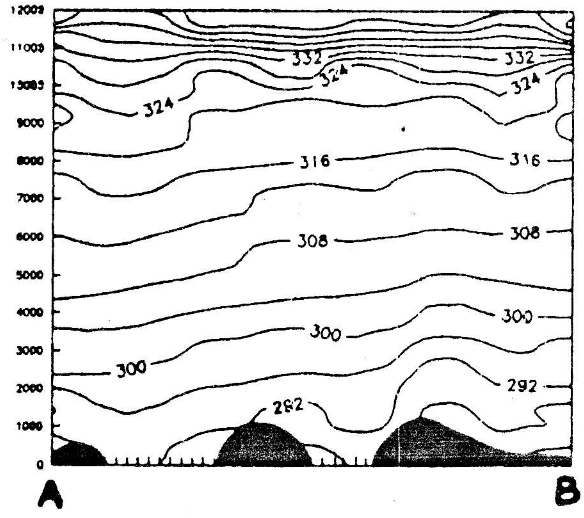


Fig.8.a Vertical space cross-section of potential temperature on 16 May 1991 at 00 UTC (the line AB in Fig.9 marks the position of the cross-section)
Sl.8.a Prostorni vertikalni presjek potencijalne temperature zraka 16.05.1991. u 00 UTC (vertikalni presjek je je rađen po liniji AB naznačenoj na sl.9)

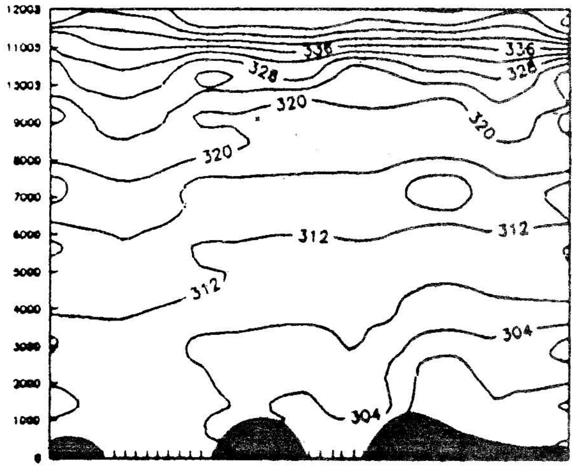


Fig.8.c Vertical space cross-section of equipotential temperature on 16 May 1991 at 00 UTC
Sl.8.c Prostorni vertikalni presjek ekvipotencijalne temperature zraka 16.05.1991. u 00 UTC (vertikalni presjek je je rađen po liniji AB naznačenoj na sl.9)

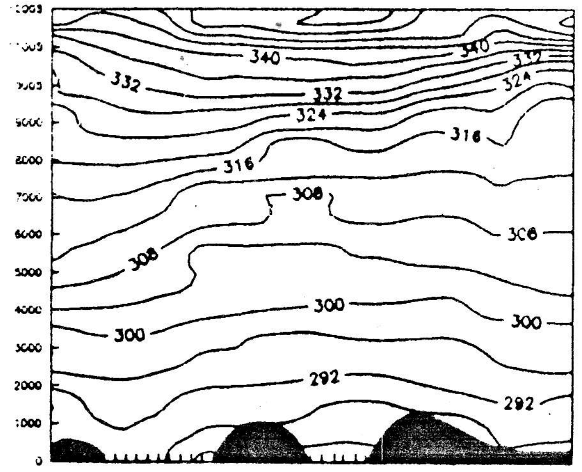


Fig.8.b As Fig.8.a but on 17 May 1991 at 00 UTC
Sl.8.b Kao na sl. 8.a, ali za 17.05.1991. u 00 UTC

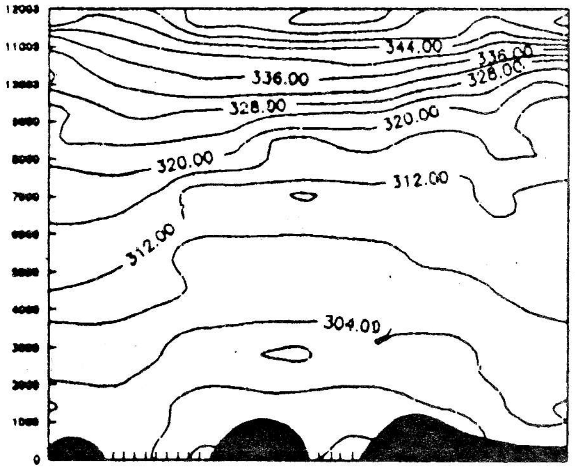


Fig.8.d As Fig.8.c but on 17 May 1991 at 00 UTC
Sl.8.d Kao na sl. 8.c, ali za 17.05.1991. u 00 UTC

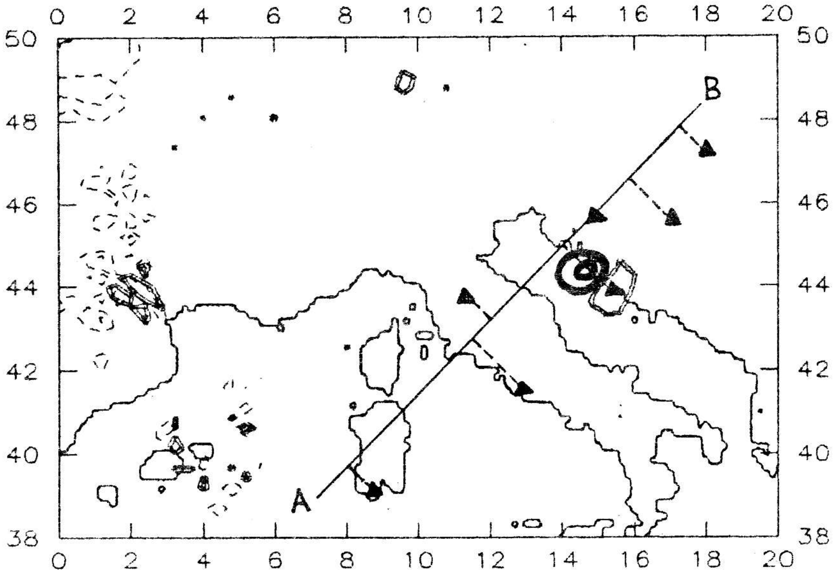


Fig.9 Local change of relative vorticity due to geostrophic advection on AT 700 hPa. 16 May 1991 at 00 UTC
... thick line: local change > 0
... double thin line: local change < 0
17 May 1991 at 00 UTC ... thin dashed line The line AB marks the position of the vertical space cross-section, while triangles mark positions of met. stations whose upper-air observations were used to obtain the cross-section.

Sl.9 Lokalna promjena relativne vrtložnosti zbog advekcije realativne vrtložnosti s geostrofičkim vjetrom na AT 700 hPa. 16.05.1991. u 00 UTC:
... puna debela linija: lokalna promjena > 0
... dvostruka tanka linija: lokalna promjena < 0
17.05.1991. u 00 UTC ... tanka crtkana linija Položaj vertikalnog presjeka označen je linijom AB, pri čemu su korištene radiosondažne postaje označene trokutićima.

occurs since compensation no longer exists with the cold air convergence at the surface (Figs. 2.a,b,c). The pressure fall on the lee side lasts as long as needed for the cold air to move over or around the barrier. During this time, in the region of pressure fall, a surface lee cyclogenesis develops due to the convergence of warm and unstable air on this side of the barrier (Fig. 3.d).

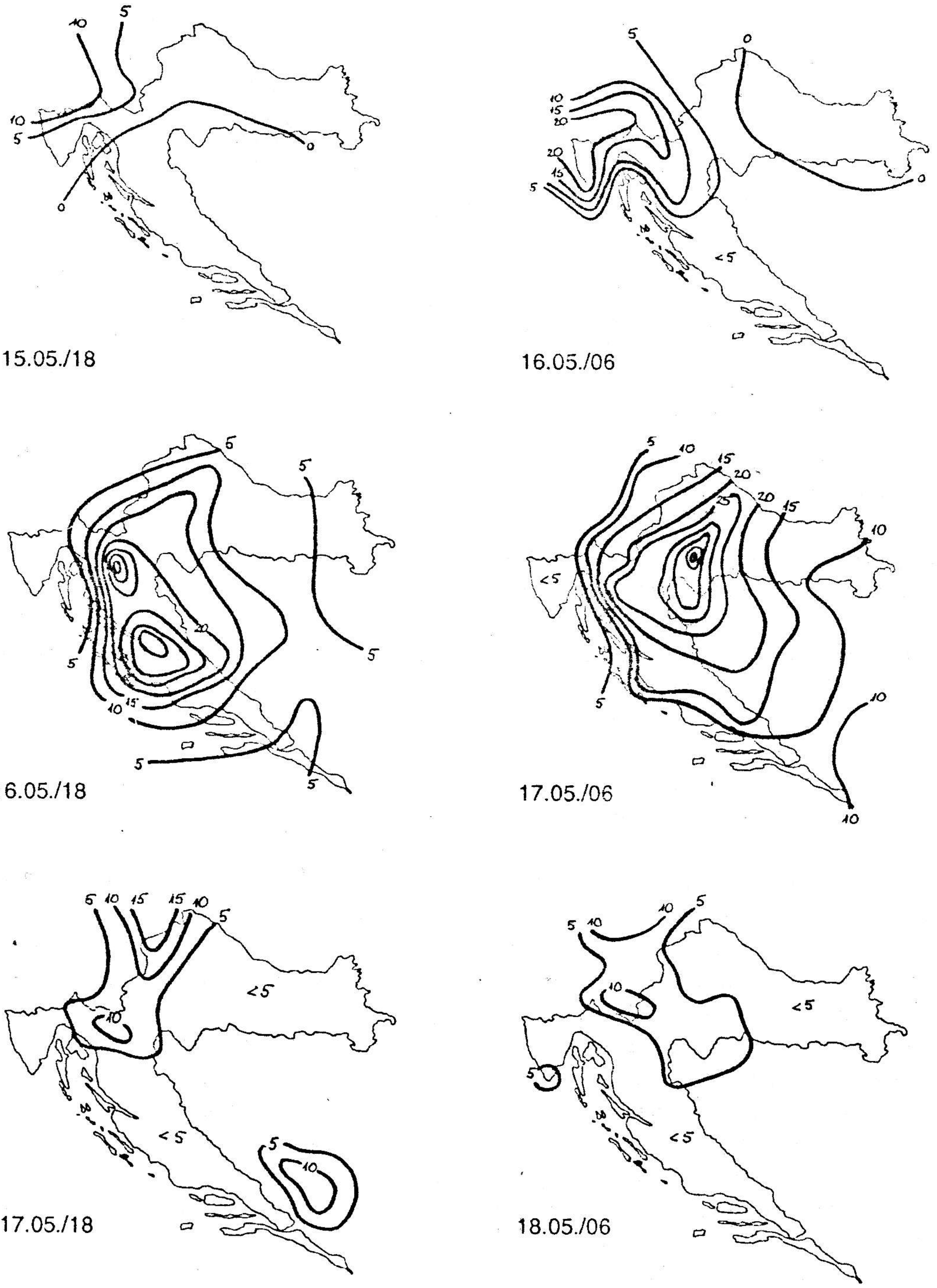
In the next stage of baroclinic cyclone development the maximum of PV moves across the mountain. This process is connected with a large relative vorticity placed above the already existing surface lee circulation.

The concept of potential vorticity and stability are rather simplified in the case of adiabatic motion. However, in the considered case of cyclone generation the important role was attributed to the diabatic effects due to the existence of a large amount of moisture (Fig.12). In such a case the thermodynamic properties of the air mass entering this process are changed, causing a weakening of the cyclone, following a large precipitation amount over the area of Croatia on 16 to 18 May.

Investigations by various authors (Reed and Albright 1986, Emanuel et al. 1987) suggest that the cyclogenesis in moist and baroclinic atmosphere could be very intensive on a subsynoptic scale.

One way of estimating probability for atmospheric instability on larger scale is the calculation of slantwise convective available potential energy - SCAPE (Shutts, 1990). In the case when the atmospheric vortex is approximately vertical, this multidimensional instability can be also introduced in the first approximation through the calculation of usual convective potential availablae energy (CAPE).

The basis for the CAPE concept is the theory of particle under the following



15.05./18 16.05./06

16.05./18 17.05./06

17.05./18 18.05./06

Fig.10 Consecutive twelve-hourly precipitation amounts over Croatia and the surrounding area on 15 to 18 May. (Precipitation units ... l/m^2)

Sl.10 Uzastopne 12-satne količine oborina od 15 do 18.05.1991. na temelju sinoptičkih postaja u Hrvatskoj, Sloveniji i Bosni i Hercegovini. Količine oborina su u l/m^2.

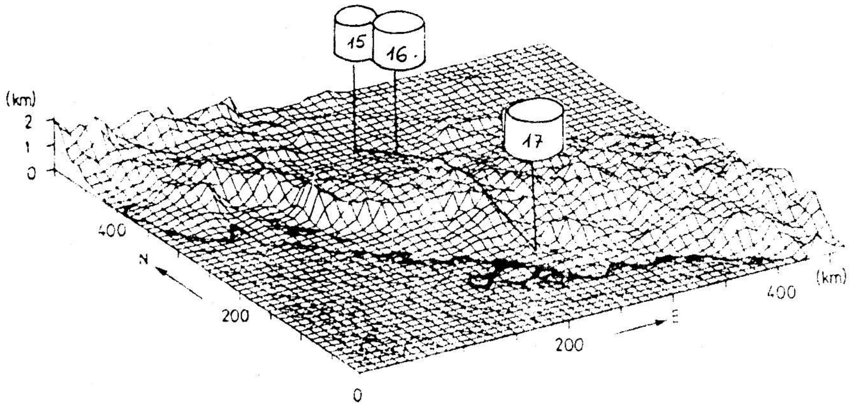


Fig.11 Translation of the local maximum of the potential vorticity between the isobaric surfaces AT 500 and AT 700 hPa on 15,16 and 17 May at 00 UTC; rollers' heights are proportional to RT 500/700, diametres to PV

Sl.11 Premještanje lokalnog maksimuma potencijalne vrtložnosti između izobarnih ploha AT 500 hPa i at 700 hPa 15.,16. i 17. 05. 1991. (00 UTC); visina valjka proporcionalna je debljini sloja RT(500/700), a radijus valjka iznosu PV

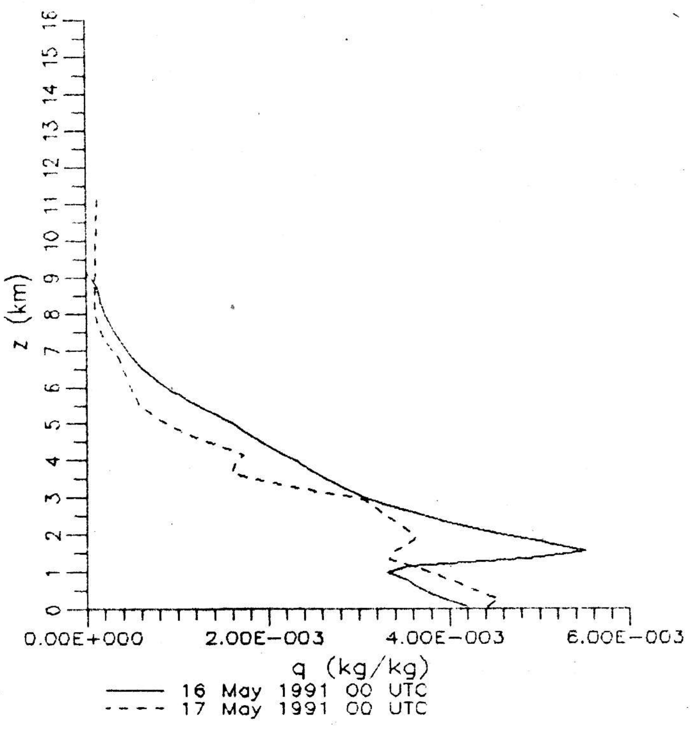


Fig.12 Vertical profiles for the Zadar station (full lines 16 May 1991 at 00 UTC, dashed lines 17 May 1991 at 00 UTC) of specific humidity (kg/kg)

Sl.12 Vertikalni profil (puna crta...16.05.1991. u 00 UTC; crtkano...17.05.1991. u 00 UTC) specifične vlage (kg/kg) prema visinskim podacima postaje Zadar-aerodrom

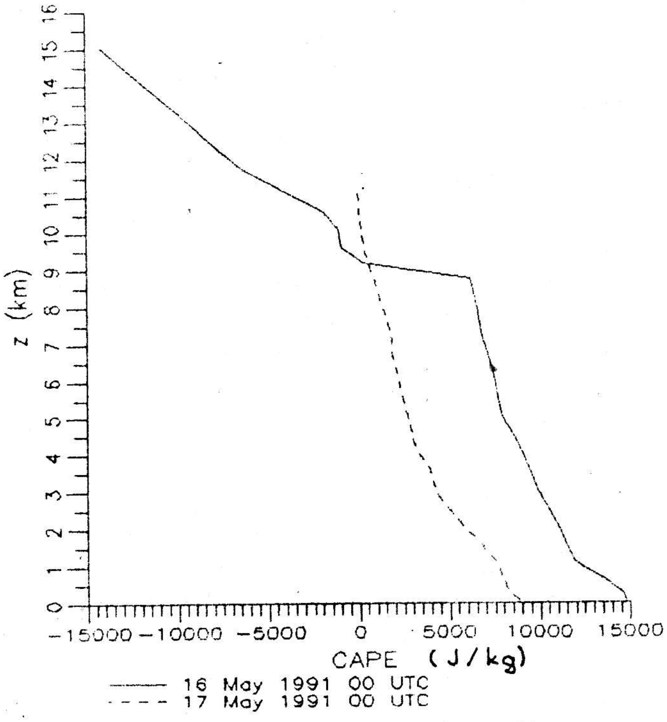


Fig.13 Vertical profiles for the Zadar station (full lines 16 May 1991 at 00 UTC, dashed lines 17 May 1991 at 00 UTC) of convective available potential energy (CAPE, J/kg)

Sl.13 Vertikalni profil (puna crta...16.05.1991. u 00 UTC; crtkano...17.05.1991. u 00 UTC) konvektivne raspoložive potencijalne energije (J/kg) prema visinskim podacima postaje Zadar-aerodrom approximations:

1) the total disturbance of the pressure gradient on the air particle is negligible,

2) the particle volume is negligible and therefore does not cause disturbance in the environmental state,

3) there is no mixing of the particle with the environment,

4) the time scale for the environmental atmosphere is on a much larger scale in comparison with the one necessary for convection.

CAPE is essentially a one-dimensional quantity based on the calculation of pressure, temperature and moisture in hydrostatic equilibrium:

$$\mathrm{CAPE} = R \int_{\mathrm{LCL}}^{\mathrm{EL}} (T_{vp} - T_v)\, d\, (\ln p)$$

Here LCL and EL are, respectively, the lifting condensation level and the equilibrium level, defined as the zero buoyancy level above the maximum buoyancy, T_{vp} is the virtual temperature of the air particle in a reversible moist adiabatic process and T_v is the virtual temperature of unsaturated moist air, following a moist pseudoadiabat (Zhang and McFarlane, 1991).

As pointed out by Zhang and McFarlane (1991), deep cumulus clouds consume convective available potential energy that is built up by other processes. Among these, low level moisture convergence and adiabatic cooling associated with the larger scale ascent are probably the most important.

It is also well-known that larger-scale upward motion is a salient feature of the response to the heating that accompanies deep moist convection.

Since the basic cause for instability is reaching the quasi-equilibrium state, we suppose that the larger-scale production of CAPE is balanced by the generation and dissipation of the kinetic energy associated with micro-scale cloud circulations. Therefore, the amount of convective available energy that exists prior to the onset of convection may be substantial larger than the minimum required to maintain cumulus cloud circulations (Fig.13).

Thus, in spite of the indicated, well-known, large-scale cyclogenesis in the Ligurian sea, the local severe storms in the Adriatic area owe their origin to the generation of an atmospheric mesoscale vortex in this area. Although originally very shallow and in most cases not observed by the regular radiosounding network, in this case the cyclone developed in its later stage, to high altitude becoming an ordinary mid-latitude cyclone.

In the considered case it was possible to follow the mesoscale process over the Adriatic area due to available soundings in Zadar. We believe, however, that many other cases exist which develop similarly. It is, on the other hand, possible that some vortices do not develop due to lack of moisture and baroclinic instability on the subsynoptic scale, and the process remains unknown on the synoptic scale. Better knowledge could be therefore expected only by additional radiosondings in the Adriatic and a denser surface network of stations which would work on synoptic observational time. Radar and satelite observations would be also necessary for their early detection. However, better understanding of these processes could be only obtained by combined studies of observational evidence and numerical simulations by mesoscale models including moist convective processes and a proper interaction with a larger-scale oreigenic cyclogenesis.

5. Conclusion

As a rule, synoptic analyses do not recognize the role of a mesoscale lee cyclogenesis over the Adriatic area, but instead diagnose only the displacement of a cyclone in an already developed stage of general macroscale geostrophic motion. Thus, severe storms in the Adriatic area are attributed to macro-scale processes which can not explain their detailed structure and generation on time and spatial scales.

Investigation of the cyclogenesis on 15-18 May 1991 indicates that the initially strongest lee vortex was registered in the Genoa bay, while the surface pressure closed low occupied the large mid-Mediterranean area. Theoretical concept of lee cyclogenesis emphasises the role of orographic cold air blocking and the simultaneous displacements of local maximum potential vorticity in higher atmospheric layers.

The presented analysis on a subsynoptic scale has discovered that the storm was related to secondary vortex generation over the Adriatic, which manifested itself through a large precipitation amount, exceptional coldness for this time of year and the late appearence of a snowstorm over the southwestern part of Croatia. The process also justifies the importance of the transformation of available potential energy produced by the larger-scale processes into kinetic energy due to exceptionally large instability on the meso- and micro-scale.

According to the present stage of knowledge this case seems to show that the cyclone was not displaced from the western Mediterranean as it is usually considered by the "cyclone tracks" across the Adriatic sea, but associated with the fast development of a mesoscale vortex over the Adriatic.

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Kratak sadržaj

U pravilu sinoptičke analize ne raspoznaju ulogu mezoskalne zavjetrinske ciklogeneze nad Jadranom, već dijagnosticiraju samo premještanje ciklone u već razvijenom stadiju u sklopu općeg geostrofičkog gibanja na makroskali. Na taj način je uobičajeno da se uzroci jakih oluja na području Hrvatske pripisuju procesima velikih razmjera koji ne mogu objasniti detaljnu strukturu i generiranje vrtloga na vremenskoj i prostornoj skali.

Proučavanje ciklogeneze 15-18. svibnja 1991. ukazuje da je početak ciklogeneze zabilježen u Genovskom zaljevu, a analiza podržava teoretski koncept zavjetrinske ciklogeneze koja naglašava ulogu orogenetskog blokiranja hladnog zraka i istovremeno premještanje lokalnog maksimuma potencijalne vrtložnosti u višoj troposferi. Međutim, analiza podsinoptičkih razmjera otkriva da je oluja bila uzrokovana stvaranjem sekundarnog vrtloga nad Jadranom, manifestirajući se kroz visoke količine oborina (Gospić 71 mm, Ogulin 138 mm) i izvanredno zahlađenje za ovo doba godine, što je uzrokovalo i pojavu snijega u Lici i Gorskom kotaru. Mezoanaliza

vertikalne strukture atmosfere bila je moguća zbog postojanja radiosondaže u Zadru neposredno prije oluje i za vrijeme oluje u samom središtu mezociklone. Ovaj proces naglašava opravdanost uvažavanja pretvorbe raspoložive potencijalne energije, koja nastaje uslijed procesa na makro-skali, u kinetičku zbog izuzetno velikih nestabilnosti vlažnog zraka u mezo i mikro razmjerima.