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ADRIATIC VORTEX GENERATION OBSERVED DURING MAP SOP AND PREDICTED BY THE MESOSCALE ALADIN/LACE MODEL

Generiranje jadranskog vrtloga za vrijeme MAP SOP i prognoza njegova razvoja mezoskalnim modelom ALADIN/LACE

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Abstract: The genesis of the Adriatic vortex and its prediction during the Mesoscale Alpine Programme Intensive Observation Period (MAP IOP) 4–5 October 1999 has been observed and this prediction is presented based on the high resolution ALADIN/LACE model. The model simulation shows that the vortex owes its existence to the Alpine circulation, similar to the one usually responsible for the large-scale lee cyclogenesis. However, the Alpine mesoscale wind field predicted three main currents following the upstream blocking and splitting processes. Two of them, around the western and eastern side of the Alps, are known from the macroscale analyses, and the third belongs to the mesoscale, appearing as an Alpine valley transverse current toward the Genoa bay. This circulation initiates the local wind systems, *bura* in the northern and *jugo* in the southern Adriatic, resulting in the generation of a mesoscale vortex after 36–42h prediction time. Another case in the following month (7 November 1999) is also illustrated when, in contrast, the Adriatic vortex was not generated by a similar type of circulation. It is shown that in this case the predicted Alpine currents are stronger, especially on the eastern side of Alps, and result in a macroscale cyclogenesis in the Tyrrhenian Sea.

Key words: Adriatic vortex, Mesoscale Alpine Programme, ALADIN model, cyclogenesis, *bura*, *jugo*

Sažetak: Prikazano je generiranje vrtloga na Jadranu za vrijeme Intenzivnog perioda motrenja mezoskalnog alpskog programa (MAP IOP) 4–5. listopada 1999. i praćena je njegova prognoza pomoću modela ALADIN/LACE velike rezolucije. Pokazano je da je vrtlog nastao kao posljedica alpske cirkulacije koja obično uvjetuje zavjetrinsku ciklogenezu. Međutim, modelirano mezoskalno polje vjetra otkriva tri glavne struje, dvije poznate iz makrorazmjera koje slijede navjetrinski bloking i razdvajanje struja oko zapadnih i istočnih Alpa, i treću mezoskalnu struju kroz dolinu Alpa prema Genovskom zaljevu. Ta cirkulacija uvjetuje lokalni sistem vjetrova, buru na sjevernom i jugo na južnom Jadranu, koji su uzrok nastanku vrtloga u prognostičkom vremenu 36–42 sata. Prikazan je i slučaj sljedećeg mjeseca (7. studeni 1999) sa sličnom cirkulacijom kada vrtlog nije nastao uz isti tip strujanja. Razlog su bila jača strujanja na području Alpa, posebno na istočnoj strani planine, što je u tom slučaju uvjetovalo ciklogenezu makrorazmjera u Tirenskom moru.

Ključne riječi: jadranski vrtlog, Mezoskalni alpski program, model ALADIN, ciklogeneza, bura, jugo

1. INTRODUCTION

Many factors that adversely affect the performance of meteorological modelling are related to both model quality and data assimilation on the mesoscale. Since large improvements in resolution have recently been made possible by an increase in computer power, a continuous model development, evaluation and intercomparison are necessary. Moreover, routine meteorological observations are usually not sufficient for both model performance and verification at scales in the meso- and smaller-scale ranges, calling for special observations in limited space and time domains.

For this reason, the Mesoscale Alpine programme – Special Observation Period (MAP SOP) was organized in 1999. with field studies in order to help establish the importance of orographic effects and to point at the gaps in our knowledge, as will be indicated in section 2. We have focused particularly on the identification of mesoscale vortices in the wind field that can be diagnosed within model-produced high-resolution fields. Such vortices in the mesoscale wind field over the Adriatic Sea are difficult to observe due to a rather scattered station network. Small-scale vortices close to the Adriatic coast were occasionally observed in the subjective analysis based on all available climatological stations in this area. One example of such an analysis in the northern Adriatic, including the islands, is given in Figure 1.

The Adriatic vortex is an intricate phenomenon since it interacts with larger- and smaller-scale flows. The first detailed analysis of this mesoscale vortex generation was presented by Ivančan-Picek (1998) using the scale separation technique. Research based on this technique has shown that such a vortex can be generated in mid-Adriatic when *jugo* prevails in the southern and *bura* in the northern Adriatic (Ivančan-Picek and Jurčec, 2002). This means that strong *bura* or *jugo* winds, when uniform along the entire eastern Adriatic coast, are not favourable for vortex generation. Vortices can be found along the frontal zone and convergence lines, but of a very small size as a short-living feature. Vortex generation was observed in the western Mediterranean by Gomis *et al.* (1990), at 850 hPa level, considering the composite of several Alpine lee cyclogenesis that occurred

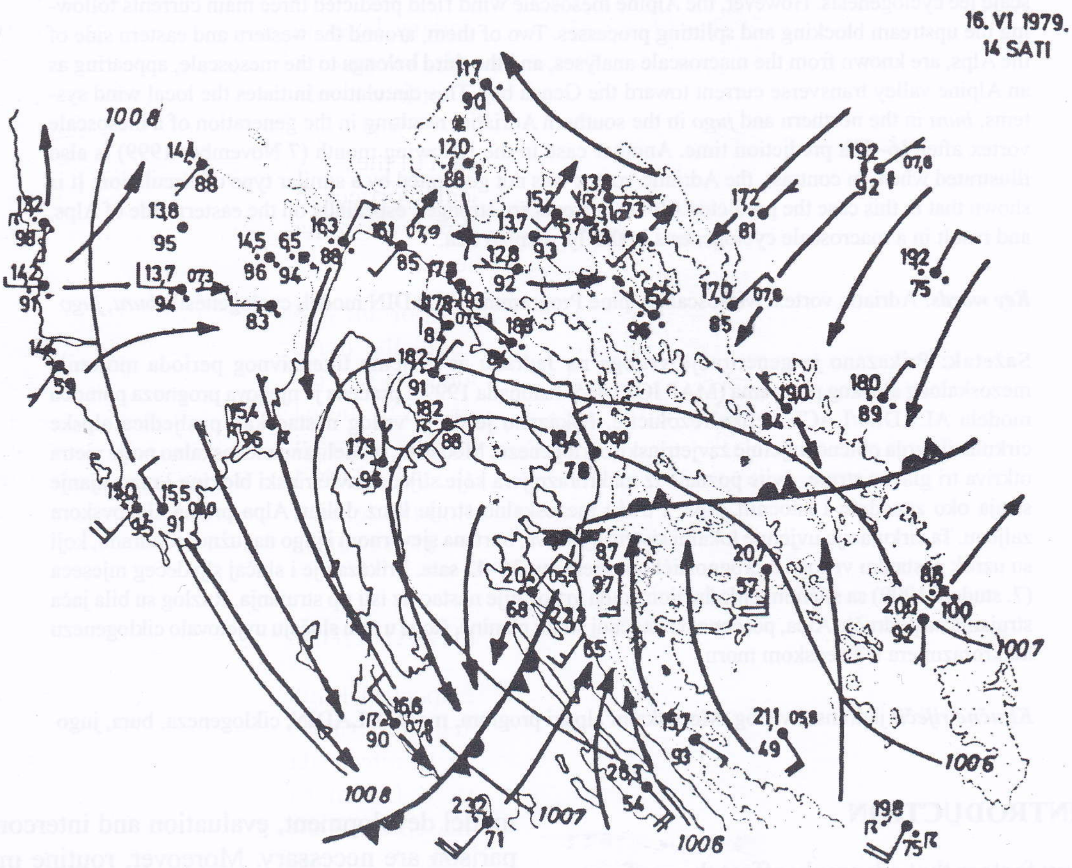

Figure 1. Mesoscale analysis of the Adriatic cyclone in the vicinity of Zadar, 16 June 1979 (Jurčec, 1983).

Slika 1. Mezoanaliza jadranske ciklone u blizini Zadra, 16. lipnja 1979. (Jurčec, 1983).

during the Alpine Experiment – ALPEX SOP in 1982.

It must be emphasized that the cyclonic vortex we observed in the wind field needs not be identical with a cyclone, particularly with a low in the pressure field during a lee cyclogenesis. As pointed out by Pierrehumbert (1986), a lee trough is caused by an adiabatic descent of air without associated cyclonic vorticity. Therefore, the decrease in pressure in the lee of the mountain does not imply cyclogenesis and pressure fluctuation is not a reliable indicator of a cyclone and a vortex existence in the wind field.

This paper discusses vortex generation as observed on the satellite images on 5 October 12 UTC, recognized by an eye and a spiral cloud structure over the mid-Adriatic, and it presents its simulation in the wind field by the high-resolution limited-area ALADIN/LACE model (Aire Limitee Adaptation Dynamique Developement InterNational / Limited Area Model for Central Europe) over the Alpine area. Our purpose is to link the Alpine mesoscale wind characteristics to the vortex appearance following an intensive local-scale convective process in the western part of Croatia on 4 October 1999.

2. THE MESOSCALE ALPINE PROGRAMME – SPECIAL OBSERVING PERIOD (MAP SOP)

The MAP is a measured response of the international atmospheric community to assemble an alpine-scale dataset suitable to advance the basic knowledge and prediction of intense weather phenomena causing considerable cost to the society in this area and other mountainous regions (Binder and Schär, 1996). This large field experiment took place from 7 September to 15 November 1999, and it was the largest field programme over the Alps since the Alpine Experiment (ALPEX) in 1982 (Küttner, 1986).

The MAP Special Observing Period (SOP) was organized into eight scientific projects (Bougeault *et al.*, 2001): 1) Orographic precipitation mechanisms, 2) Incident upper-tropospheric PV anomalies, 3) Hydrological measurements and flood forecasting, 4) Dynamics of gap flow, 5) Non-stationary aspects of foehn in a large valley, 6) Three-dimensional gravity wave breaking, 7) Potential vorticity banners, and 8) Structure of the planetary boundary layer over steep orography.

The aim of this project was to further our basic understanding and forecasting capabilities of the physical and dynamical processes that determine 3-dimensional circulation patterns in the vicinity of large mountain ranges, and to focus on the key orography-related mesoscale effects that are exemplified in the Alpine region (Binder and Schär, 1996).

Statistical evaluation has shown that the year 1999 was a very good year relative to the frequency and distribution of MAP-relevant weather events. 17 IOPs were conducted, totalling 42 days of activity. Our case studies are related to IOP5 (2–4 October) and IOP15 (5–9 November) and they are connected to the boundary layer problem which significantly affects flow past topography, including the generation of low-level vortices (Thorpe *et al.* 1993). Low-level topographic flow anomalies downstream of the Alps manifest themselves as mesoscale vortices that range from the prediction of low-level convergence to that of lee cyclogenesis.

An important MAP task is to systematically validate the performance of high-resolution models and to assess the quality of regional forecasts in the Alps and surrounding area. In this context we will examine the performance of the ALADIN/LACE high-resolution prediction model in the study of low-level vortex generation over the Adriatic Sea.

3. THE ALADIN/LACE MODEL

The spectral limited area model for the presented numerical simulation is the ALADIN (Aire Limitee Adaption Dinamique et Development International) initiated by Meteo-France in 1990 and developed in co-operation with the National Meteorological Services of several European countries and Morocco (Bubnova *et al.*, 1995; Brzović and Jurčec,1996; Brzović *et al.*, 1997). It is running operationally throughout the central European area with a resolution of 12.2 km to satisfy the needs of

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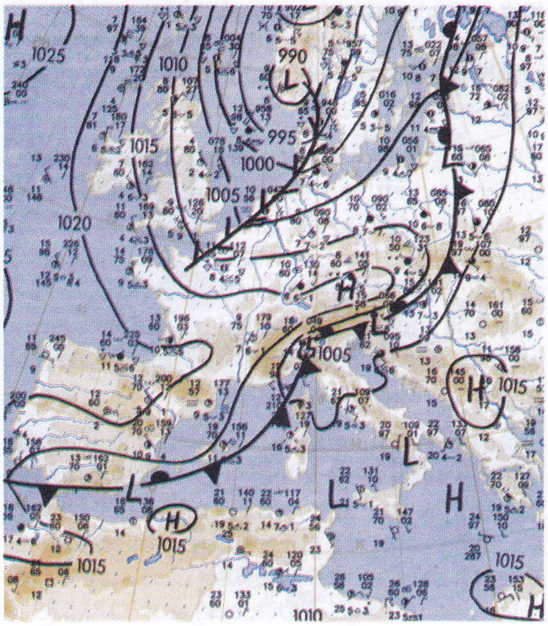

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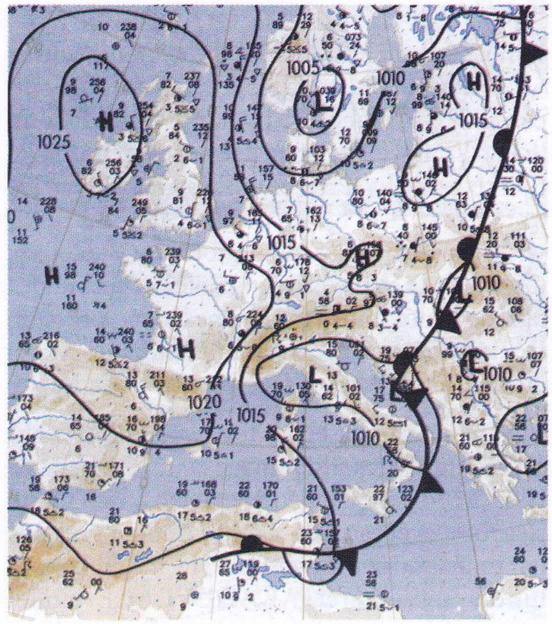

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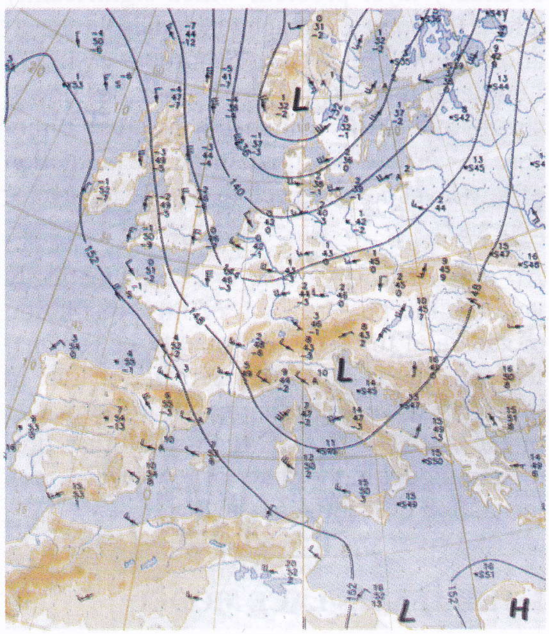

Figure 2. Synoptic charts, October 1999 (MAP IOP 5: a) October 4, 00 UTC; b) October 5, 00 UTC, c) October 4, 12 UTC, 850 hPa. (From the Meteorological Bulletin of Deutscher Wetterdienst)

Slika 2. Sinoptičke analize, listopad 1999 (MAP IOP 5: a) 4. listopada, 00 UTC; b) 5. listopada, 00 UTC, c) 4. listopada, 12 UTC, 850 hPa. (Meteorological Bulletin of Deutscher Wetterdienst)

LACE (Limited area Central European countries) for high resolution forecasts. From 1996, the ALADIN/LACE model has been running operationally twice a day for 48 hours, centred over the Central European region. The Meteorological and Hydrological Service of Croatia joined the ALADIN project in 1995 and this model is now used in both research and operational work with a resolution of 8 km.

The present structure of the model (Bubnova *et al.*, 1995), as part of the French global model ARPEGE/IFS (Integrated Forecasting System), takes the initial and lateral boundary conditions from the operational ARPEGE results by interpolation with the 6-hour frequency of coupling.

4. SYNOPTIC OVERVIEW AND ADRIATIC VORTEX APPEARANCE

Well-known cases of Alpine cyclogenesis contain a blocking and splitting flow in the upstream area of the Alps. The intensity and direction of wind in this area dictate the position and intensity of the lee cyclone. Strong NW winds will likely lead to a more intense southerly current on the western side of the Alps and a strong cyclogenesis in the western Mediteranean. Relatively weaker westerly winds will further influence the current around the eastern Alps and lead to a cyclogenesis in northern Italy

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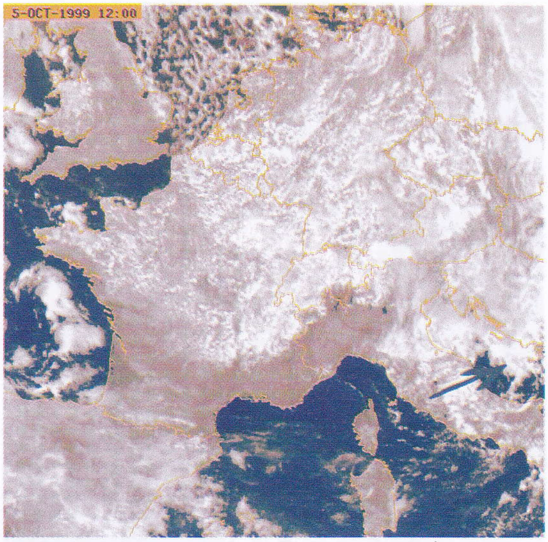

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Figure 3. METEOSAT satellite images for 5 October 1999, 12 UTC: a) visible (VIS) image – the arrow marks cyclonically curved lines of cumuli; b) water vapour (WV) image – the arrow marks dry intrusion (from MAP Data Centre).

Slika 3. Satelitske slike METEOSAT-a za 5. listopada 1999., 12 UTC: a) vidljiva slika (VIS) – strelica pokazuje ciklonalno zakrivljenu liniju kumulusa; b) slika vodene pare (WV) – strelica pokazuje prodor suhog zraka iz viših slojeva atmosfere (iz MAP Data Centre).

or on the Adriatic sea. The latter case offers also chance for an Adriatic vortex generation as we will show in our case study.

Figure 2 shows the synoptic charts on 4–5 October 1999. The surface chart on 4 October shows a typical blocking on the northern side of the Alps and a weak lee cyclone along the front in the north of Italy. The main cyclonic activity is seen in Scandinavia, and it is rapidly weakening on 5 October. The frontal system moved on that day to the east with a weak cyclone in mid-Adriatic. The next day (not shown), this cyclone was still in the Adriatic but even weaker, and the front was already in the eastern Balkan. On 850 hPa level, on 4 October, a deep trough was extending from Scandinavia to the mid-Mediterranean. Strong N winds were over Great Britain, but W winds were on the northern and western side of the Alps, preventing a stronger blocking and splitting flow on the northern side of the Alps.

Thus, the result of a relatively weak synoptic forcing was an inactive stationary cyclone associated with the frontal system. Unfortunately, lack of surface observations over the sea prevented us from verifying the real position and the state of the considered cyclone. However, during that time we followed the METEOSAT satellite images over the Adriatic Sea. The *small scale vortex* can be seen in Figure 3a, in visible (VIS) imagery. It is particularly important to note that even when the WV image indicates a very dry upper troposphere, there may well be moist air near the surface. The dry slot, visible on the WV images, is associated with a cyclogenesis and high potential vorticity (Bader *et al.*, 1995). The Water Vapour (WV) imagery (Fig. 3b) shows a well-defined descending tongue of dry air (the “dry intrusion”) observed as a dark band over Italy and the mid-Adriatic.

Since we had studied the intense atmospheric processes on 4 October on the eastern side of the Alps, it was clear that the apparently weak development on the synoptic scale over the Adriatic area was quite different in strenght from the smaller mesoscale and local-scale weather in the considered event where the steep mountain ridges of the Dinaric Alps helped to release the conditional instability. This strong process, with a high precipitation amount is

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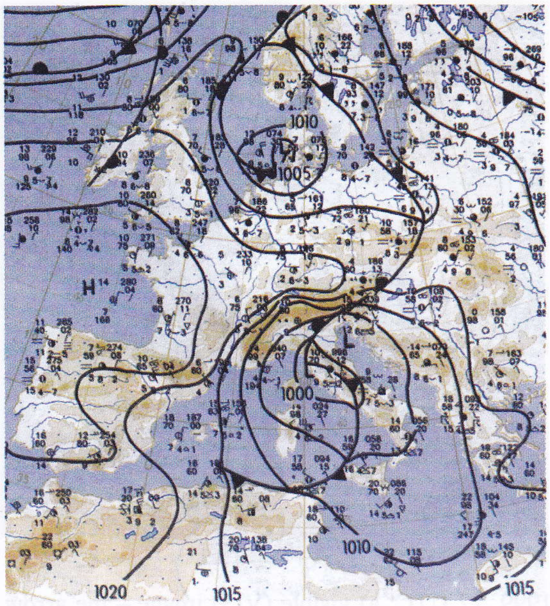

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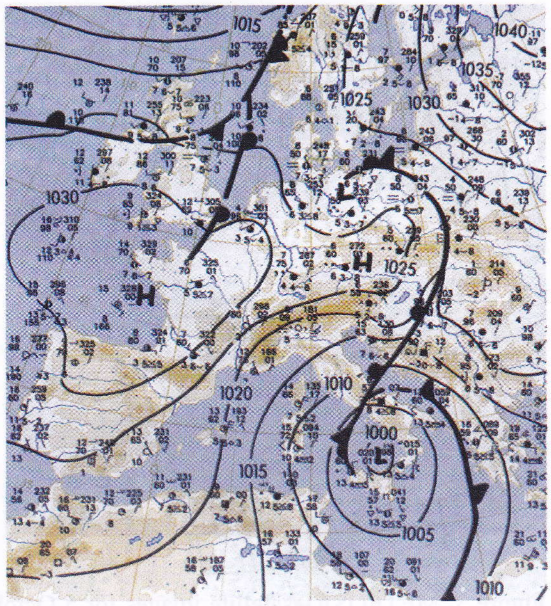

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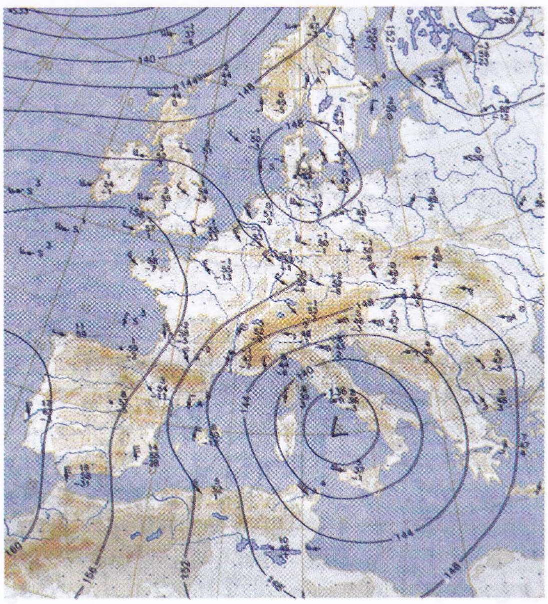

Figure 4. Synoptic charts, November 1999 (MAP IOP 15: a) November 7, 00 UTC, b) November 8, 00 UTC, c) November 7, 12 UTC, 850 hPa. (From the Meteorological Bulletin of Deutscher Wetterdienst)

Slika 4. Sinoptičke analize, studeni 1999 (MAP IOP 15: a) 7. studenoga, 00 UTC, b) 8. studenoga, 00 UTC, c) 7. studenoga, 12 UTC , 850 hPa. (Meteorological Bulletin of Deutscher Wetterdienst)

described in detail in another paper (Ivančan-Picek *et al.*, 2002) containing the vertical time cross-sections by HRID (High Resolution Isentropic Diagnosis) based on available 3- and 6-hourly time intervals of radiosoundings in this area during the MAP IOP5. However, before discussing the contribution of numerical prediction, we will briefly mention a similar case study during IOP15, which did not lead to an Adriatic vortex generation.

On 7 November (Fig. 4), there was a relatively weak low south of Scandinavia, whereas high pressure covered south-western Europe. The low in the northern Adriatic in Figure 4a was not found the next day. Instead, a deeper low in the Tyrrhenian Sea was now the main feature on both surface and 850 hPa charts.

5. RESULTS OF THE ALADIN/LACE MODEL'S PREDICTION

We are here presenting the results of the ALADIN/LACE models available from the MAP Operational Centre. The prediction of the Adriatic vortex generation is based on the initial time of 00 UTC, on 4 October 1999, about 36 hours before the vortex appearance. Figure 5 illustrates the horizontal wind field at 500 m after 6, 12, 24, 30, 36 and 42 hours. Initially, the flow encountering the Alps was relatively weak and flowing westerly from the Atlantic. When reaching the Alps, the wind turned to the south, toward the west Mediterranean. After 6 hours, we find in the Genoa bay the usual picture of a weak lee cyclonic circulation with SW winds turning through mid-Italy toward the Adriatic Sea. This influenced the *jugo* wind on the Croatian coast.

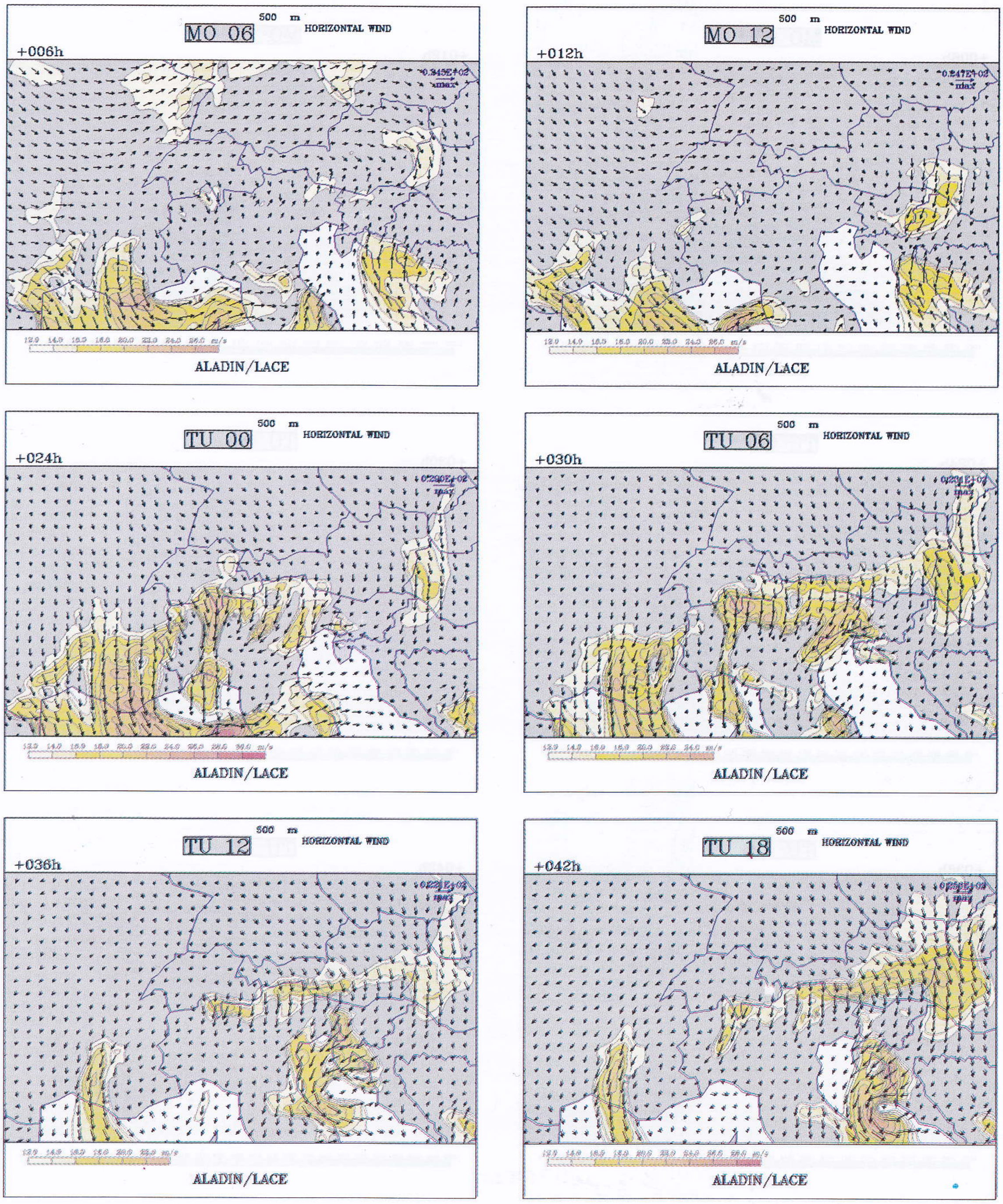

Figure 5. Mesoscale 500 m wind forecast by ALADIN/LACE (MAP IOP 5) after 06, 12, 24, 30, 36 and 42 hours. Initial time October 4, 1999, 00 UTC. Wind speeds above 12 ms^{-1} are shaded.

Slika 5. Prognoza vjetra na 500 m mezomodelom ALADIN/LACE za MAP IOP 5 nakon 6, 12, 24, 30, 36 i 42 sata. Početno vrijeme integracije 4. listopada 1999., 00 UTC. Brzine vjetra iznad 12 ms^{-1} osjenčane su.

From 6 to 12h of prognostic time, the west winds on the northern side of Alps turned to the south flowing around the eastern flanks of the Alps. Reaching the border between Croatia and Slovenia, a strong convergence occurred between the NE *bura* flow and the SE *jugo* winds leading to the formation of a rainband with convectively unstable air and a large pre-

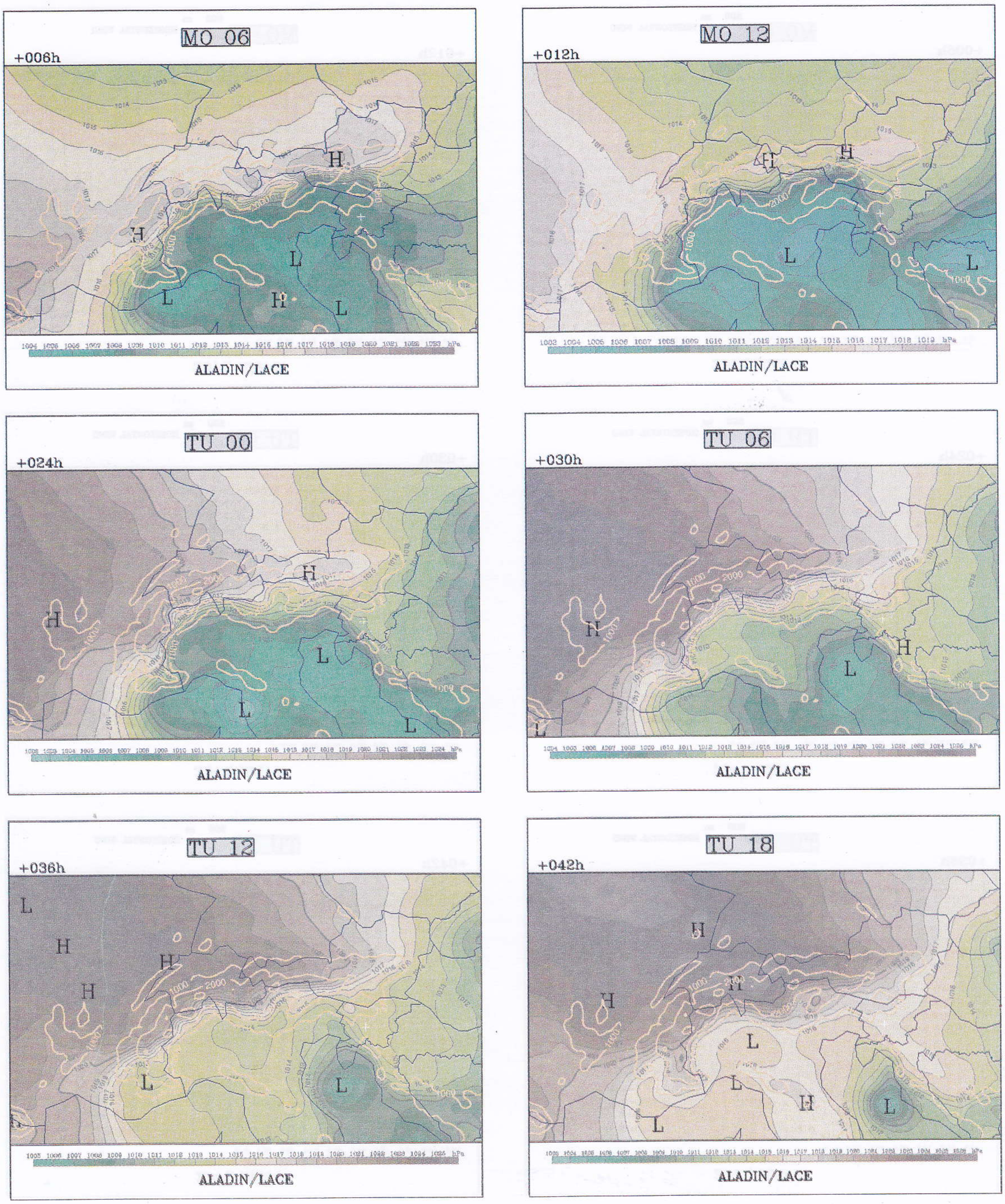

Figure 6. Mesoscale sea level pressure forecasting by ALADIN/LACE (MAP IOP 5). Prediction times as in Figure 5. Isolines 1 hPa each.

Slika 6. Prognoza prizemnog polja tlaka zraka mezomodelom ALADIN/LACE za MAP IOP 5. Izolinije su dane svakih 1 hPa. Termini kao na slici 5.

cipitation amount resulting from the earlier mentioned extraordinary event in western Croatia.

During the next 12 hours, at 24h of prognostic time, the essential mesoscale current in the Alpine area was the one *through* the valley transverse sections in the direction of the Genoa bay, which is not seen on the synoptic scale chart. At the same time, SW winds in this area intensified toward the mid-Adriatic. At 30h, a NE *bura* flow was noticed in the bay of Trieste, on the north Adriatic coast. This intensified the cyclonic circulation in the northern Adriatic leading to the *generation of a cyclonic vortex at 36h of prognostic time*, which is still clearly seen at 42h in mid-Adriatic.

Figure 6 presents the corresponding mesoscale forecast of the pressure field for the same time periods. During the first day, the main features were a high pressure area on the northern and western side of the Alps and several smaller-scale low centres on the lee side. After 24 hours of prediction time there was a low centre in the northern Adriatic, slowly moving to the south-east. The last two charts, at 36h and 42h, show this low in the centre of the cyclonic vortex shown in Figure 5. This means that the vortex is balanced and does not show the ageostrophic characteristics emphasized in the earlier analysis for mesoscale vortices (Ivančan-Picek and Jurčec, 2002; Gomis *et al.*, 1990). The model's results show a strong pressure gradient across the Dinaric Alps, leading to intense local winds, *bura* and *jugo*.

Finally, we will briefly show the results of the model's prediction in the second case, MAP IOP15, based on the initial analysis of November 6, 1999, 00 UTC. Figure 7 shows the 24h and 36h forecast of wind and pressure fields. After 24h, the wind field is again characterized by three currents in the Alpine area, as in the first case. However, the winds are stronger here, in the western Alps, as well as in the middle current through the Alpine valleys toward the Genoa bay. This current weakens at 36h while the *bura* flow intensifies in the northern Adriatic toward the Tyrrhenian cyclone seen in Figure 4. During the next 12 hours, the *jugo* wind from the 24h map over the Adriatic turns to E-ESE and intensifies. There is no pronounced vortex on the Adriatic, although a weak cyclonic circulation can be seen in mid-Adriatic.

The circulation in this case, as opposed to the first one, is caused by a stronger pressure gradient over the Alpine area. Also, in comparison with the first case, there are no small-scale lows. This means that the generation of the Adriatic vortex prefers a weaker circulation in the

a) b)

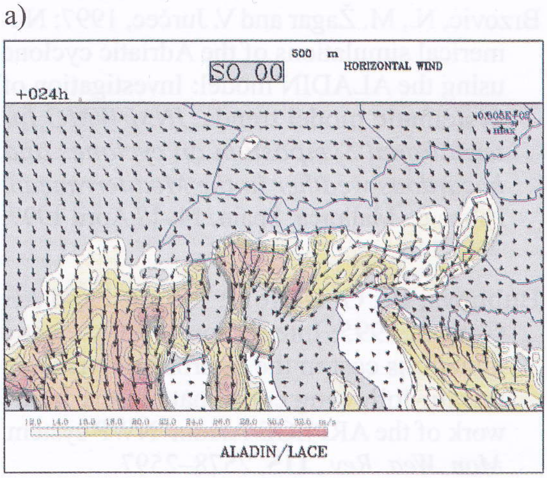

Figure 7. Mesoscale 500 m wind (a) and sea level pressure (b) forecasting by ALADIN/ LACE (MAP IOP 15). Initial time November 6, 1999, 00 UTC. Forecast for 24 and 36 hours of prediction time. Wind speeds above 12 ms^{-1} are shaded. Isolines 1 hPa each.

Slika 7. Prognoza vjetra na 500 m i prizemnog polja tlaka zraka mezomodelom ALADIN/LACE za MAP IOP15 nakon 24 i 36 sata. Početno vrijeme integracije 6. studenoga 1999., 00 UTC. Brzine vjetra iznad 12 ms^{-1} osjenčane su. Izolinije u polju tlaka zraka dane su svakih 1 hPa.

Alpine area, although locally both *bura* and *jugo* winds can temporarily be strong.

6. SUMMARY AND CONCLUSION

The Adriatic vortices belong to a rich range of mesoscale phenomena influenced by Alpine orography. Due to the lack of suitable observational data over the open Adriatic Sea, a basic understanding and successful prediction of these phenomena are very difficult.

The case of vortex generation on 4 October 1999 described in this paper occurred during the MAP SOP, with an increased data set available and enhanced forecasting capability addressing the meso- and smaller-scale weather phenomena, as well as the most recent numerical tools.

The considered vortex generation followed an intense convective process on the eastern side of the Alps during IOP5, when a large amount of surface data and radiosoundings for 3- and 6-hourly periods were available. The vortex was noticed by the METEOSAT satellite images on 5 October, at 12 UTC, as a mesocyclonic vortex with an eye and spiral cloud structure over the mid-Adriatic.

The ALADIN/LACE mesoscale high-resolution prediction model successfully indicated the location of the vortex generation at that time. It is emphasised that the three main currents over the Alpine region were responsible for the genesis of this vortex. Two of them, around the eastern and western side of the Alps, are known from the large-scale flow field following the upstream blocking and splitting process. The third current appears in the mesoscale wind field as the cross-Alpine flow confined to valley transverse sections toward the Genoa bay. The vortex generation therefore represents a link between intense smaller-scale local weather and a relatively weak larger scale synoptic forcing.

Another case of similar Alpine circulation, but with much stronger currents, is illustrated for 7 November (IOP15). It did not result in the genesis of an Adriatic vortex, but in a strong and deep cyclogenesis on the Tyrrhenian Sea.

It is hoped that the results of this MAP cases will add to a better understanding of future studies of the Adriatic vortex generation, taking into consideration the link between the different scales and flow intensities, from the local and meso- weather scale to large-scale synoptic forcing.

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