Classification of Cyclone Tracks over the Apennines and the Adriatic Sea

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ABSTRACT

Cyclones that appear in the Adriatic Sea basin strongly influence the climate and weather conditions in the area. In particular, apart from the usually mild climate, cyclone activity in the Adriatic and the central Mediterranean Sea provide both the main hydrological forcing and the trigger mechanisms for a range of extreme weather phenomena. Therefore, a basic understanding of the cyclogenesis over the Adriatic Sea is essential. In particular, the classification of different types of cyclogenesis in the area is fundamental because it will help the understanding and prediction of the relevant weather phenomena. In this study, based on the analysis of the 4-yr (2002–05) operational European Centre for Medium-Range Weather Forecasts T511 dataset, various types of cyclone tracks are classified and the mesocyclogenesis areas in the vicinity of the Adriatic Basin are isolated. This analysis indicates that the following four types of cyclogenesis over the Adriatic Sea can be identified: 1) type A: cyclones connected with preexisting Genoa cyclones [with two subcategories, (A-I) continuous track: Genoa cyclones crossing over the Apennines to the Adriatic Sea, and (A-II) discontinuous track: new surface cyclones generated over the Adriatic Sea under the influence of a parent cyclone generated in the Gulf of Genoa (Genoa cyclones) and moving toward the Adriatic but blocked by the Apennines]; 2) type B: cyclones developed in situ over the Adriatic Sea without any connections with other preexisting cyclones in the surrounding area; 3) type AB: mixed types A and B cyclones, including cases where two cyclones coexist and stride over the Apennines (twin or eyeglass cyclones); and 4) type C: cyclones moving from the Mediterranean Sea, but not from the Gulf of Genoa (non-Genoa cyclones) [with 2 subcategories: (C-I) continuous track: a non-Genoa cyclone is able to cross over the Apennines to the Adriatic Sea continuously, and (C-II) discontinuous track: a non-Genoa cyclone is blocked by the Apennines and a new surface cyclone is generated over the Adriatic Sea]. The relevant dynamics of the above types of cyclones are discussed along with characteristics of the cyclones and their synoptic situations at the lower and upper troposphere.

1. Introduction

The Adriatic Sea is a mesoscale northwest–southeast elongated basin in the central Mediterranean Sea, which is approximately 200 km wide and 1200 km long and almost entirely enclosed by high mountains (Fig. 1): the Apennines to the west and southwest, the Alps to the north, and the Dinaric Alps to the east and southeast. The area usually enjoys a mild climate, but cyclone activity in the Adriatic and the central Mediterranean provides a trigger mechanism for a range of extreme weather phenomena, such as local downslope windstorm bora, or *bura* in Croatian (e.g., Smith 1987; Klemp and Durran 1987; Bajić 1989; Jurčec 1989; Ivančan-Picek and Tutiš 1996; Grubišić 2004; Belušić et al. 2004; Gohm and Mayr 2005), strong winds called sirocco and tramontana (Jurčec et al. 1996; Cavaleri et al. 1999; Pandžić and Likso 2005), heavy orographic

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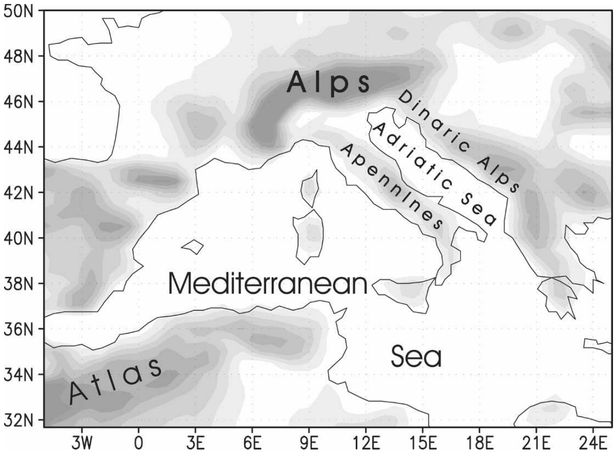

FIG. 1. The western and middle Mediterranean with sites of interest mentioned in the text. The area corresponds to an ECMWF T511 resolution model orography in the domain. The terrain contour interval is 200 m, starting from 200 m.

precipitation, thunderstorms, supercells, and mesoscale convective systems (Ivančan-Picek et al. 2003). The geomorphology of the terrain and viscous energy transport may then, in turn, cause storm surges in Venice, Italy (Trigo and Davies 2002; Lionello 2005), flash floods (De Zolt et al. 2006), high seas (Leder et al. 1998), avalanches, and landslides (Lionello et al. 2006). However, despite the development of sophisticated high-resolution numerical mesoscale models, weather in the broad area of the Alpine lee (the Apennine and Adriatic regions) is still characterized with limited predictability, especially of mesoscale and submesoscale processes. For these reasons, field experiments such as the 1982 Alpine Experiment (ALPEX; see Kuettner 1986) and the 1999 Mesoscale Alpine Program (MAP; see, e.g., Bougeault et al. 2001) were designed to conduct meteorological measurements in the Adriatic region to allow for validation and error assessment of numerical models. Therefore, investigations of different cyclone types in the region and assessment of associated weather conditions, including extreme weather, are of a great importance not only for the improvement of weather forecasting but also for a more complete understanding of weather and climate impacts in the Mediterranean.

The climatology of Mediterranean cyclone activities has been investigated in a considerable number of studies. Early subjective studies recognized the Gulf of Genoa as the main Mediterranean cyclogenesis area (van Bebber 1891; Pettersen 1956). Such subjective synoptic studies dominated the early research until the appearance of model-based datasets and objective cyclone detection and tracking algorithms. Such objective synoptic-scale classifications (with model resolution > 1°) commonly identified major cyclogenesis areas, such as the Gulf of Genoa, Cyprus, northwest Africa, and the Iberian Peninsula, as well as secondary ones such as southern Italy and the Aegean Sea (e.g., Alpert et al. 1990a; Trigo et al. 1999; Campins et al. 2000; Maheras et al. 2001). In a few recent mesoscale studies, other centers, such as the Pyrenees and the Adriatic, Alboran, and Balearic Seas, have been detected (Picornell et al. 2001; Gil et al. 2003; Campins et al. 2006).

Because of the scales of the Adriatic Basin and the surrounding complex terrain, cyclogenesis in the Adriatic Sea was traditionally inadequately detected by subjective synoptic analysis. The encouraging attempts of a subjective subsynoptic analysis in the central Mediterranean (Radinović 1965, 1978; see Radinović 1987 for a review) indicated the existence of two rather separate areas of cyclone activities, the northern and middle Adriatic regions. However, Radinović's studies only covered a very short duration of time (1 yr of surface data) and did not include surface data over the Adriatic Sea. Recent synoptic-scale objective studies focused on larger Mediterranean cyclogenesis centers (e.g., Trigo et al. 1999; Maheras et al. 2001; Picornell et al. 2001; Gil et al. 2003) and presented a spectrum of Adriatic-related results. While most of the studies did not refer to the Adriatic as a prominent Mediterranean cyclogenesis center, some studies nevertheless identified the Adriatic as the major area of explosive deepening in the cold season (Conte 1985; Maheras et al. 2001). Using similar objective analysis with higher-resolution model (basin well-resolving) datasets, the northern Adriatic was identified as a region of high cyclone activity (Campins et al. 2000, 2006; Picornell et al. 2001).

However, the reliability of the current state-of-the-art objective algorithms diminishes as the resolution of complex terrain increases (A. Genoves and J. Campins 2006, personal communication). For the entire western Mediterranean, significant variations for many important subsynoptic-scale or mesoscale cyclogenesis centers were shown in different studies in terms of the overall number of cyclones and their seasonal density (the Pyrenees, the Adriatic, inland Algeria, southern Italy, etc.). Many of these mesoscale cyclogenesis centers are located in proximity to mesoscale mountain ranges. Therefore, there is little doubt that these differences are caused to some extent by the resolutions of the different datasets. However, it appears that the most significant mesoscale discrepancies come from different cyclone classification and tracking algorithms, where a certain degree of subjectivity and strong biases might be introduced by the choice of the algorithm details. An illustrative example showed that even with the same objective criteria, a simple Cressman smoothing, which is used in many climatology studies, can reduce the number of cyclones by an order of 10 and completely eliminate some strong cyclogenesis centers (Gil et al. 2003).

In addition, circulation is often not strictly defined in the cyclone detection and tracking criteria. Although mean sea level pressure (MSLP) and vorticity showed similar results for cyclone identification on the synoptic scales (Hoskins and Hodges 2002), significant differences in cyclone circulations were present in the analysis of mesoscale cyclones. An airstream passing a mesoscale mountain may produce either a pressure low in the lee, but without closed circulation, or, on the contrary, a vortex without the pressure low (see, e.g., Lin 2007). Since the study of the cyclone activity in the Adriatic has to include meso-β scales (20–200 km), an algorithm based solely on the MSLP might in turn introduce significant biases in the analysis. On the other hand, vorticity and circulation are very noisy on the mesoscale, which makes implementation of circulation criteria into the algorithm extremely difficult (Campins et al. 2006).

Yet another characteristic of the Adriatic area is the fact that the majority of cyclones that appear in the basin actually traverse the Apennines from the west. This circumstance, rather unique in the Mediterranean area, has two important consequences. The surface low pressure weakens and may first disappear completely over the mountain peaks, because of the presence of mountain-induced high pressure, and then reappear in the lee. This, in turn, may cause the overestimation of the deepening rates and the cyclone first-appearance climatology in the lee of the Apennines. This kind of behavior is known from fluid dynamics and has been documented for midlatitude cyclones crossing the Rocky and Appalachian Mountains (e.g., Chung et al. 1976) and for tropical cyclones crossing the Central Mountain Range of Taiwan (Lin et al. 2005). Second, the cyclone may become discontinuous over the mountain range, with two separate vorticity centers simultaneously present over the mountain. Once the parent cyclone disappears on the upstream side of the mountain, the lee daughter cyclone may strengthen, replace the parent cyclone, and then resume the original track. This type of cyclone continuity analysis can have a noteworthy influence on the results of the climatology study in complex terrain (e.g., O'Handley and Bosart 1996). Thus, the Adriatic-oriented objective track algorithm needs to take into account the processes associated with the cyclone passage over the mountain so as not to overestimate either the number of cyclogenesis events or the associated deepening rates over the lee of the Apennines.

Because of the discussed complexity of a reliable objective scale- and geomorphology-dependent algorithm in the inherently mesoscale area of interest, we choose to conduct a manual analysis fully devoted to the cyclone activity in the Adriatic Basin. Furthermore, the focus on a smaller region gives more information on less frequent cyclone types and tracks, thus providing a complete picture of the cyclone activity in the area.

The results show the typical cyclone tracks related to the Adriatic area as well as the climatology of the intrinsic Adriatic cyclogenesis. In addition, typical cyclone cases belonging to isolated cyclone tracks will be shown and discussed. In this fashion, the cyclone climatology and the cases presented will serve as a platform for the subsequent analysis of precipitation patterns associated with the different cyclone tracks in the Adriatic. [A similar study has been performed in the case of tropical cyclones crossing Taiwan (Witcraft et al. 2005; Lin et al. 2002).] In addition, this climatology study will be a background for future numerical modeling and analysis of the Adriatic cyclones. In section 2, data and methodology will be described. Classification of Adriatic cyclones will be presented in section 3, and their characteristics will be discussed in section 4. Conclusions and remarks are made in section 5.

2. Data and methodology

A manual subjective analysis technique was used to analyze the cyclone activity over the Apennine and Adriatic areas. In addition, the subjective analysis included objective guidance regarding the MSLP intensity and cyclone duration, while circulation criteria remained predominantly subjective. The present work is based on the 4-yr (2002–05) T511 operational analysis data with 6-h temporal resolution, acquired from the European Centre for Medium-Range Weather Forecasts (ECMWF). Of the available model data archives, this dataset allows for the highest spatial resolution in the related midlatitudes (~40 km).

As the first step, an occurrence of pressure lows was identified based on the MSLP 2-hPa closed isobar, either in the wider Adriatic region (approximately 100 km around the basin) or traversing the area. Then, streamlines were analyzed to identify the associated circulation pattern in the area of pressure low. If the pressure low was above the sea or flat land, closed circulation cyclone identification was required. However, if the cyclone was shallow or in the vicinity of the moun-

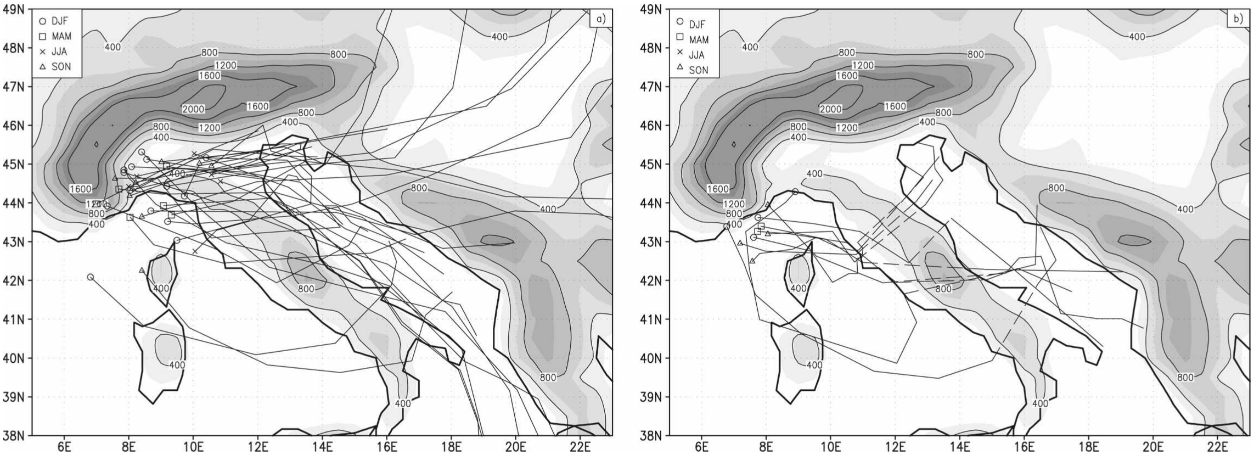

FIG. 2. Track plots of Genoa (a) type A-I continuous and (b) type A-II discontinuous cyclones. Most of the A-I cyclones cross the Apennine peninsula in the north, while most of the A-II cyclones traverse to Adriatic over the middle Apennines.

tains, a strong surface convergence (significant streamline curvature) pattern was recognized. This type of streamline pattern is often present during the process of cyclone initiation in mountain areas as well as during its passage over the mountain range. Particularly where complex terrain strongly modifies the surface circulation (as in cases of weak cyclone initiation of the Alpine lee over northern Italy), strong surface convergence was taken as a sufficient criterion for cyclone detection as long as the system satisfied objective MSLP thresholds. This choice kept the analysis somewhat subjective but more in accordance with conceptual models as well as with other climatology studies. Once a cyclone was detected in the area of interest, it was back-traced (traced) to its place of origin (its deterioration or exit out of the domain).

With respect to the project goal discussed in the introduction, the subjective cyclone detection and tracking criteria were aimed at isolating somewhat more significant and intense cyclones (both in terms of duration and intensity) that are more important for the weather and climate in the region. In accordance, objective constraints included a 2-hPa closed isobar lasting at least 6 h for all cyclones that appear in the Adriatic. However, very few cyclones were added to the classification, even if it did not fully satisfy the above MSLP closed isobar criteria. These exceptions belong to the twin cyclone type, discussed in the next section, in which the secondary center is sometimes well defined in the vorticity field but not in the pressure field. In several such cases, at least a 1-hPa closed secondary pressure low was required.

We designed these criteria in accordance with the spatial and temporal dimensions of the cyclones identified in operational practice, conceptual models, and Adriatic cyclone case studies (e.g., Radinović 1987; Ivančan-Picek 1998; Brzović 1999). In particular, these types of mean sea level and circulation thresholds aim at improving the identification of cyclone initiation and tracking in the lee areas of the Alps and Apennines through a dedicated regional cyclone analysis.

3. Classification of Adriatic cyclones

Based on the selected classification criteria, several types of cyclones that appear in the Adriatic Basin and their associated tracks were detected and classified as the following types:

1) A: Genoa cyclones (the Gulf of Genoa and northern Italy),
    (a) A-I: continuous Genoa cyclones,
    (b) A-II: discontinuous Genoa cyclones;
2) B: Adriatic cyclones,
    (a) B-I: northern Adriatic cyclones,
    (b) B-II: middle Adriatic cyclones,
3) AB: simultaneous Genoa and Adriatic cyclones (twin or eyeglass cyclones);
4) C: non-Genoa and non-Adriatic cyclones,
    (a) C-I: continuous cyclones,
    (b) C-II: discontinuous cyclones.

Most of the cyclones that appear in the Adriatic are cyclones that originate in the Gulf of Genoa or northern Italy. These are commonly referred to as Genoa or Alpine lee cyclones and are here identified as type A cyclones (Figs. 2a,b). This reflects the fact that in winter the area is the most active cyclogenesis region in the western Mediterranean (e.g., Trigo et al. 1999). Indeed, in our study the Genoa cyclones that occur in winter [December–February (DJF)] are twice as frequent as those in other seasons (Table 1). This result resembles the outcome of several subjective studies (e.g., Radinović 1965; Campins et al. 2000). On the other hand, a number of objective studies (Campins et al. 2000, 2006; Maheras et al. 2001) indicated that summer is the main season for Genoa cyclone activity. It thus might be that deeper winter cyclones steered by the upper-level trough have a stronger preference to traverse the Apennine range, while shallow summer cyclones are more stationary and have their paths along the western Apennine coast. However, regardless of the results of our study, it appears that different treatment of the summer lows was applied in the subjective and objective analyses, resulting in the differing results. Note that a cyclone may also move to a new location because of the upper-level forcings.

The two main subtypes of type A Genoa cyclones that traverse the Adriatic were detected according to their continuity over the Apennine mountain range. Most of the Genoa cyclones initiate over the lee of the continental Alpine mountain range, close to the Gulf of Genoa, and retain their continuity during the traversal over the peninsula (type A-I). These cyclones usually cross the northern, lower-elevation part of the Apennines along the Po Valley to the northern Adriatic where the tracks start to diverge (Fig. 2a). While the main branch slides down the Adriatic Basin, a subset of cyclones cross the northern Dinaric Alps and follow less well-defined eastward or northeastward subtracks. In addition, a number of shallower cyclones experience cyclolysis and do not propagate further. Occasionally, Genoa cyclones move along the western Italian coast to the Tyrrhenian Sea before crossing the peninsula to the Adriatic Basin. It is interesting to note that these Genoa cyclones are initiated solely over the seawater of the Gulf of Genoa (not above the continent of northern Italy) and usually traverse to the Adriatic over the higher-elevation parts of the Apennines—preferably the middle Apennines (with the highest peak, Monte Corno, at 2912 m). Such a cyclone track results in two separate MSLP and circulation centers that are present simultaneously on both sides of the mountain. In a subsequent development, the windward center typically experiences cyclolysis and the lee center strengthens and eventually replaces the parent cyclone. Although the temporal resolution of the dataset is rather coarse with respect to the advection time scale over the mountain, such processes were identified over the Apennines, constituting the type A-II Genoa cyclones (Fig. 2b). It is anticipated that the number of discontinuous cases would increase with an increase of the time resolution of the reanalysis dataset.

TABLE 1. Seasonal variability of the cyclone types in the Adriatic region detected in period 2002–05.

	A-I	A-II	B	AB	C-I	C-II	Total
December–February	14	4	10	3	14	3	48
March–May	6	2	6	2	11	2	29
June–August	7	0	11	1	1	1	21
September–November	8	4	7	2	10	1	32
Total	35	10	34	8	36	7	130

Discontinuous cyclone tracks over higher mountains were well documented in cyclone climatology studies (e.g., O'Handley and Bosart 1996; Lin 2007). In those studies, the influence of the Appalachian mountain range on cyclonic weather systems showed that most of the cyclones undergo redevelopment as they traverse over the range, with a high variation of exact redevelopment location. Similarly, roughly half of the cyclones crossing the middle Apennines show a discontinuity feature as they traverse the Adriatic Basin. The location where discontinuous A-II cyclone tracks traverse the Apennines shows the importance of the mountain range height for the process. In other words, in a region with considerable mountain height, such as the Apennines, cyclone tracks are more likely to be discontinuous. This implies that a criterion for the discontinuity over the middle-latitude mountain ranges might be evaluated in terms of the vortex Froude number, as done for tropical cyclones crossing over Taiwan (Lin et al. 2005).

The results show that 11 Genoa cyclones annually traverse the Apennine peninsula to the Adriatic, constituting more than 35% of the total number of cyclones detected in the region. This number at first sight seems to be exceedingly small compared to the number of Genoa cyclones detected in recent objective classifications. However, this difference is mostly explicable in terms of the Genoa cyclone track diffluence upon initiation: the first track slides to the west of the Apennines to the Ionian Sea and the second over the Apennine peninsula to the Adriatic, and only the latter track is of interest to this study.

In addition, according to Trigo et al. (1999) and Picornell et al. (2001), about 60% of cyclones in the Mediterranean last for less than 12 h. According to the same studies, approximately half of all Genoa cyclones are shallow cyclones that do not reach much higher than 850 hPa (Campins et al. 2006, their Fig. 4). These studies characterize shallow summer Mediterranean cyclogenesis by the prevailing thermal forcing and diurnal variations, implying an intrinsic quasi-stationarity.

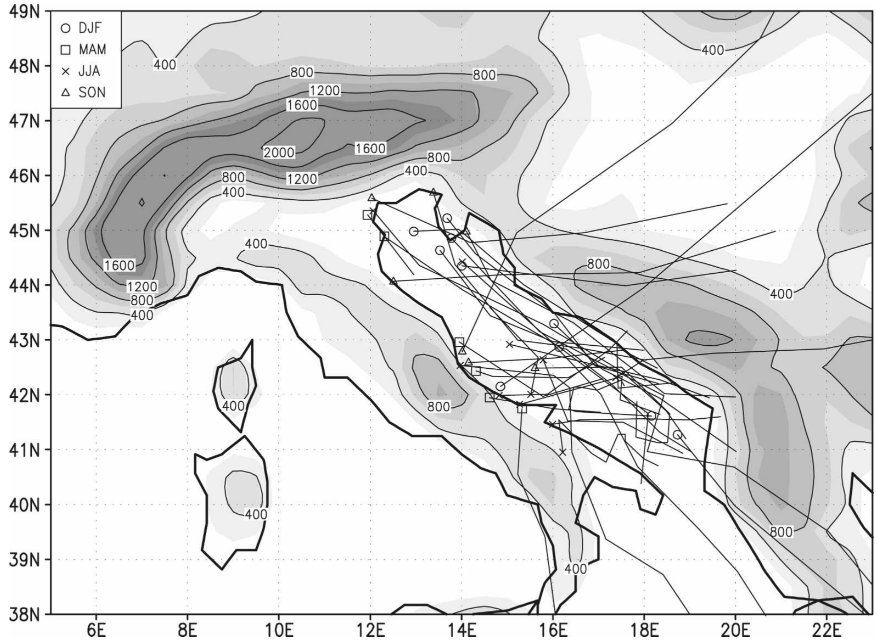

FIG. 3. Track plots of Adriatic cyclone types: type B-I cyclones move from north to south along the Adriatic Sea and type B-II cyclones initiate in the lee of the middle Apennines and traverse the Adriatic almost perpendicular to the main basin axes.

Moreover, a number of studies have rather loose pressure criteria and identify open lows as cyclones as well. Thus, the criteria of closed circulation and 6-h closed 2 hPa isobar significantly reduced the number of identified cyclones in our study. Having all of the above in mind, by applying some simple conceptual numbers we can easily speculate that the number of Genoa cyclones identified in other studies should be at least several times greater than the number of Genoa cyclones active in the Adriatic. The identified cases under these criteria can be compared with the results of Trigo et al. (1999, their Fig. 7), who identified approximately 35 cyclogenesis cases lasting for more than 12 h in the Gulf of Genoa annually. Indeed, practically all of the Genoa cyclones identified in our study lasted for at least 12 h, which is often the time period necessary for a Genoa cyclone to appear in the Adriatic. Another comparison can be made with the results of Campins et al. (2006, their Fig. 4) that identified 80 cyclones in the Gulf of Genoa annually. If we assume that on average it takes a cyclone 12 h to leave the Gulf of Genoa area, which is the approximate duration of the first phase of Genoa cyclone development (e.g., Buzzi and Tibaldi 1978), the yearly number of cyclones in their study would be around 40. In a different approach, an observational study during the ALPEX period (Pichler and Steinacker 1987) identified 43 Genoa cyclones in 13 months. Therefore, the comparison with our results implies that approximately 25%–30% of Genoa cyclones traverse the Apennine peninsula to the Adriatic Sea.

It is important to note that in our study we clearly separated the cyclones that were advected to the Gulf of Genoa from those that originated in the region. This is especially important both for a comparison with cyclone appearance statistics presented in other climatology studies and for operational practice, where sometimes this fact is overlooked. Because of high baroclinicity near the northern Mediterranean coast (e.g., Reiter 1975), many preexisting winter cyclones follow the coastal lines and reach the Gulf of Genoa. Thus, a study that detects only the presence of cyclones might show a greater number of cyclones detected in the lee of Alps than the actual number of cyclones that originated in the area.

Figure 3 and Table 1 indicate that, in terms of the annual cyclone frequencies, the Adriatic Sea is a stronge mesocyclogenesis area. The resulting type of intrinsic Adriatic cyclone is classified as a type B cyclone in this study. Two major subtypes and tracks of intrinsic Adriatic cyclones are detected and contribute to 25% of the total number of detected cyclones in the region (Table 1). The first subcategory of type B cyclones (i.e., type B-I) initiates in the lee of Alps in the northern Adriatic Sea and moves southeastward along the basin. This type of cyclone seems to be qualitatively similar to the Genoa cyclones that move along the western Italian coast over the Tyrrhenian Sea. Most of these cyclones are generated in the colder season of the year, with cyclone tracks along the Adriatic Basin channeled between the Apennines to the west and Dinaric Alps to the east.

The second subcategory of Adriatic cyclones (i.e., type B-II cyclones) originates in the lee of the middle Apennines and quickly traverses the Adriatic almost perpendicular to the basin. This type of cyclone has a considerably shorter lifetime scale and is less intense than the northern Adriatic type. The cyclone longevity and cyclolysis seem to be highly constrained with the Dinaric Alps mountain range. Most of these cyclones occur in the warmer season of the year, which implies that in addition to orographic effect, heat fluxes from the sea might be strong cyclogenetic factors. It should be noted that the number of cyclones detected would be much higher if a circulation criterion were not applied. Our subjective analysis often identified 1-hPa pressure lows in the lee of the middle Apennines. These types of lows are a common feature of the middle Adriatic area and are often markedly decoupled from the vorticity centers (Ivančan-Picek 1998), not satisfying the cyclone detection guidance imposed in our study. Thus, if MSLP cyclone criterion is the only criterion used (i.e., there is no vorticity criterion), the middle and the southern Adriatic might appear to be more intense cyclogenesis centers than the northern Adriatic. This might have impacted the results of the several objective studies that covered both regions (e.g., Trigo et al. 1999; Picornell et al. 2001). On the other hand, both ours and Radinović's (1987) subjective analysis show similar cyclogenesis intensity for both the northern and middle Adriatic areas.

There is an indication of a third group of cyclones that originate in the Adriatic region, which appears to be attached to the western coast of the middle and southern parts of Dinaric Alps. In contrast to the northern part, the mountain height increases southward (the highest point, Maja Jezercë, is 2692 m). The geographical characteristics of the genesis region of these cyclones imply that these cyclones are lee cyclones of the Dinaric Alps. In addition, the convergence of the local winds known as *bura* and *jugo* (a mountain-channeled sirocco wind) appears to be a generating factor for these cyclones and will be discussed in the next section.

In general, despite their high genesis frequency, Adriatic cyclones are usually rather weak compared to Genoa cyclones. While type B-I cyclones can occasionally reach significant deepening rates, type B-II cyclones rarely deepen more than 4–5 hPa throughout their Adriatic life cycle (refer to the discussion in section 4). Probably for this reason, a well-defined genesis location of type B-II cyclones was not clearly identified in earlier studies.

Occasionally, two cyclones simultaneously exist—one over the Gulf of Genoa and the other over the northern or middle Adriatic Sea. These cyclones are called twin or eyeglass cyclones in the literature (e.g., Brzović 1999) and are classed as type AB in this study (Fig. 4). On average, this type of rather rare event occurs less than twice a year according to our analysis. Typically, the twin cyclones simultaneously move from northwest to southeast along the western Italian coast and the Adriatic Sea, respectively. Alternatively, the Adriatic member of the twin cyclone crosses the Dinaric Alps and moves to the east. Type AB has not been identified in up-to-date climatology studies, although it is well known to forecasters in the region and has already been numerically analyzed (to be discussed later). While both twin cyclone centers can be identified, it is more appropriate to treat them as one structure because they belong to the same system in the upper levels, similar to binary (e.g., Ziv and Alpert 1995) or discontinuous cyclones (e.g., Lin et al. 2005).

Both because there are many fewer type AB cyclones than types B-I and B-II and because the Adriatic twin cyclones most often move from the northern to the southern part of the basin, there is no significant net effect of type AB cyclone climatology on the comparison of relative frequencies of cyclone appearances in different parts of the Adriatic Sea. Nevertheless, for completeness, the type AB cyclone will be added in the Adriatic area cyclone climatology.

A non-Adriatic and non-Genoa type of cyclone is classified as a type C cyclone, which initiates farther to the west (Figs. 5a,b). These cyclones form in several cyclogenesis areas of the western Mediterranean, such as the Pyrenees, Iberia, the Atlas Mountains, the Alboran Sea, and the Atlantic Ocean, as well as over the Mediterranean seawater mass. They contribute to about 35% of the total number of cyclones detected in the Adriatic area. These cyclones can often reach fierce intensities and cause a range of severe weather events as they move over the Mediterranean (e.g., Horvath et al. 2006). While these cyclones often occur in the wintertime, the most noteworthy fact is the very limited number of type C cyclones present in the Adriatic during the summer. It is well known that summer cyclogenesis in the western Mediterranean is dominated by the Iberian thermal effect, with no predominant upper-level influence. Notably, our results show that most of these cyclones do not traverse to the Adriatic area. This is in accordance with some earlier studies (e.g., Trigo et al. 1999, their Fig. 11) that show that the main western Mediterranean summer cyclone tracks follow the

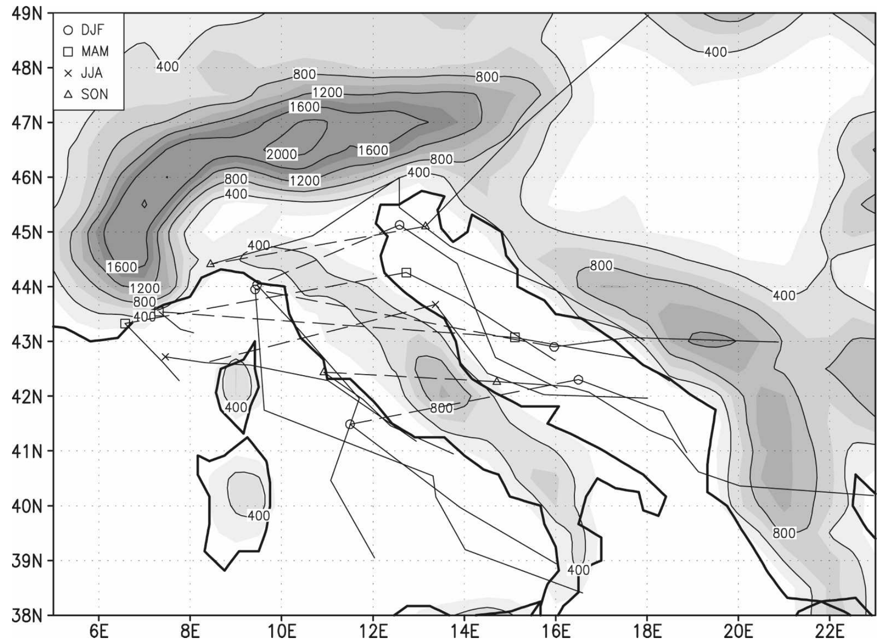

FIG. 4. Track plots of type AB twin or eyeglass cyclones with two coexisting cyclonic centers: the first in the Adriatic Sea and the second in the Gulf of Genoa (or Tyrrhenian Sea). The centers usually move along the main peninsula axes.

northern Mediterranean coast and end near Genoa Bay. This might imply that shallow Iberian summer cyclones may not protrude into the Adriatic because of summer westerly and northwesterly winds over the Gulf of Genoa and the Tyrrhenian and the Adriatic Sea regions. Hence, it appears that the lack of upper-level steering flow and the predominant etesian summer circulations are the two dominant factors influencing the cyclone tracks in the region.

Similar to Genoa cyclones, the majority of type C cyclones cross the Italian peninsula to the Adriatic Sea with no significant signs of discontinuity (type C-I; Fig. 5a). However, some type C cyclones become discontinuous and experience redevelopment over the Apennine mountain range (type C-II; Fig. 5b). It should be noted that if the cyclones follow the wintertime high baroclinic zone of the northern Mediterranean coast, they often experience redevelopment over the Gulf of

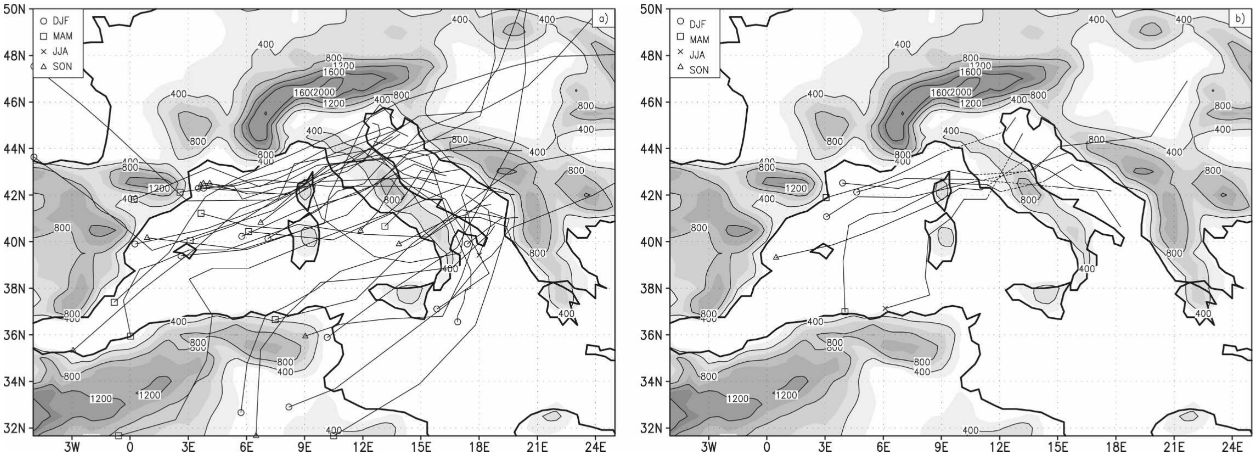

FIG. 5. Track plots of non-Adriatic and non-Genoa (a) type C-I continuous and (b) type C-II discontinuous cyclones. These types of cyclone initiate in the areas of the Pyrenees, Iberia, the Atlas Mountains, the Alboran Sea, and the Atlantic as well as over the Mediterranean.

Genoa, which leads to difficulties in cyclone categorization. In addition, remnants of Atlantic cyclones at the end of the Atlantic storm track occasionally enter the Mediterranean and often redevelop over the sea. Thus, a chain-like series of cyclone redevelopments over the western Mediterranean longitudinally increases the complexity of track analysis.

The analysis of B-I, B-II, and AB cyclones indicates a similar number of cyclogenesis cases in the northern and middle Adriatic. Similarly, the total number of cyclone appearances in these regions is approximately the same. That is, the number of Genoa and B-I cyclones not entering the middle Adriatic Sea seem to be approximately equal to the number of B-II and Genoa cyclones entering the middle Adriatic (but not the northern Adriatic), resulting in no significant net effect. At the same time, locations of type C cyclone traversal to the Adriatic are uniformly distributed over the peninsular axes. In addition, it is interesting to note that the usual northwest–southeast cyclone track along the Adriatic Basin converges with the Genoa cyclone track along the western Italian coast. Partly for this reason, and partly because of the common existence of pressure lows (as discussed above), this region of southern Italy and the southern Adriatic was identified as a pronounced center of the cyclone activity (Alpert et al. 1990a,b; Maheras et al. 2001).

4. Characteristics of cyclone types

In this section we will show the typical cases of the isolated cyclone tracks and discuss their properties, restricting the analysis to Adriatic and Genoa cyclones only. Since these track types (with the exception of type A-I) did not receive much attention in terms of diagnostics or analysis, we will propose and briefly discuss the associated genesis factors.

a. *Type A—Genoa cyclones*

The Genoa or Alpine lee cyclone is one of the Mediterranean cyclone types that have received the most attention in literature. Numerous studies verified that Alpine lee cyclogenesis is a two-phase process (e.g., Buzzi and Tibaldi 1978; McGinley 1982). The first phase is associated with cold front retardation, a cold air outbreak into the Mediterranean Sea, and the rapid creation of a shallow vortex in the Gulf of Genoa. The second phase exhibits traditional baroclinic development and the interaction between lower- and upper-level vortices (e.g., Hoskins et al. 1985).

A Genoa cyclone with continuous track (type A-I) took place on 3 March 2003 (Figs. 6a,b). As an upper-level, shortwave streamer (Massacand et al. 1998; Hoinka et al. 2003) advected over the Alps, a vortex was created near the southwest edge of the mountain ridge. This part of the lee is characterized by both a mountain-scale warm anomaly and a low-level potential vorticity near the primary banner and the edge of the wake (not shown). This seems to be consistent with the recent findings that argue that the low-level PV anomaly created by flow deformation on the obstacle might have a significant influence on the initiation and localization of a lee cyclone (Aebischer and Schär 1998), just as a thermal anomaly does. The finding theoretically follows from the invertibility principle (Hoskins et al. 1985), which states that any vortex contributing to the second phase of lee cyclogenesis could be either a thermal anomaly or a low-level PV anomaly.

Upon generation, the cyclone crossed the Italian peninsula to the northern Adriatic over the northern Apennine mountains and the Po Valley, in coherence with advection of the upper-level disturbance (Figs. 6c,d). In general, the diffluence of Genoa cyclone tracks upon generation and at a later stage is primarily influenced by the upper-level flow steering, but also seems to be modified by diabatic effects. In particular, numerical simulations of an ALPEX case showed that convection seems to drift the Genoa cyclones to the east and northeast, while surface heat fluxes tend to move it toward the warmer southeast water bodies (Alpert et al. 1996). Thus, it appears that latent and sensible heat fluxes from the sea might have played an important role in influencing the track. In subsequent hours, the cyclone was steered to the southeast and moved along the basin in a typical northwest–southeast path (Figs. 6e,f). This type of cyclone often causes severe weather events in the Adriatic. More specifically, a strong sirocco wind (the *jugo*) usually blows along the basin from the southeast in front of the cyclone, while a northeasterly downslope bora develops after the frontal (cyclone) passage. Thus, a region of strong *jugo* typically moves southeastward, thereby creating favorable conditions for a bora to develop initially on the northern Dinaric Alps and then spread over toward the southern Dinaric Alps. The typical convergence of these two wind systems might contribute to cyclone deepening (Ivančan-Picek 1998). In the latter phase of cyclone development, a deep and well-defined Genoa cyclone left the Adriatic Basin and continued its life cycle in the Ionian Sea.

Genesis locations and mechanisms of type A-II Genoa cyclones with discontinuous tracks are similar to those of type A-I Genoa cyclones with continuous tracks (Figs. 7a,b). Upon generation on 1200 UTC 5

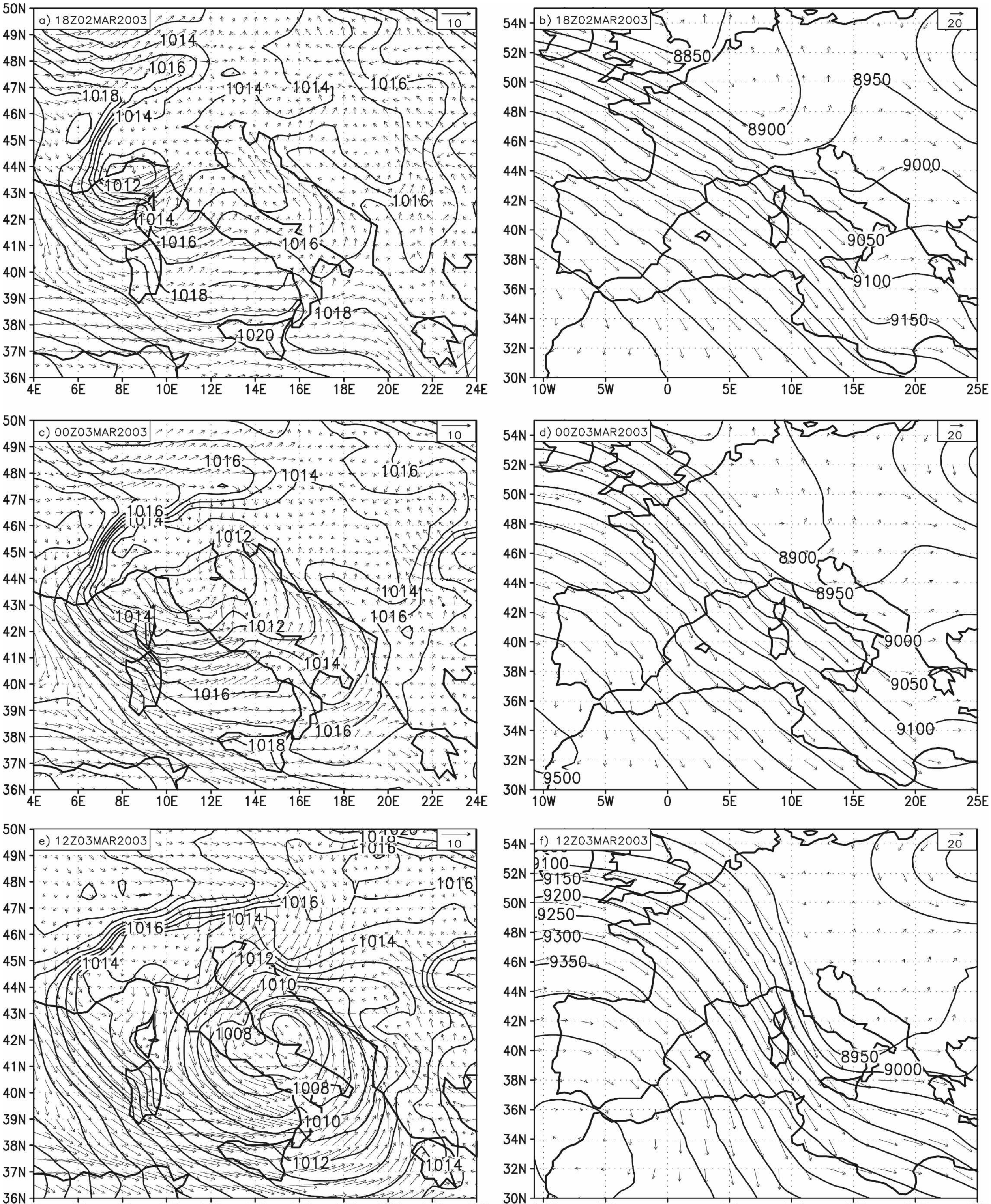

FIG. 6. A continuous Genoa cyclone (type A-I) (left) surface MSLP and wind fields and (right) geopotential and wind fields at 300 hPa on (a),(b) 1800 UTC 2 Mar 2003, (c),(d) 0000 UTC 3 Mar 2003, and (e),(f) 1200 UTC 3 Mar 2003.

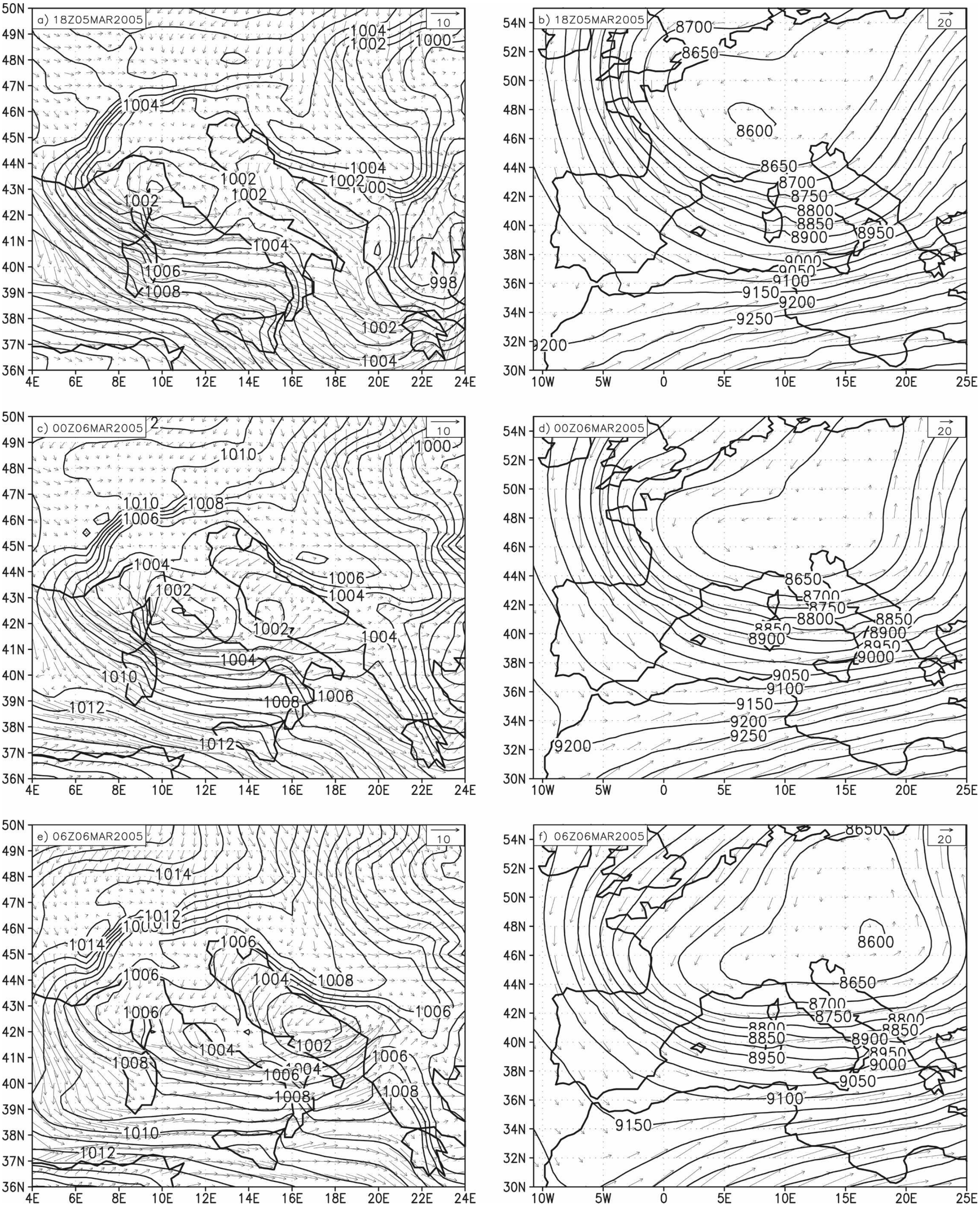

FIG. 7. A discontinuous Genoa cyclone (type A-II) (left) surface MSLP and wind fields and (right) geopotential and wind fields at 300 hPa on (a),(b) 1200 UTC 5 Mar 2005, (c),(d) 0000 UTC 6 Mar 2005, and (e),(f) 1200 UTC 6 Mar 2005. At the last time instant shown, a new cyclone is already forming in the Gulf of Genoa.

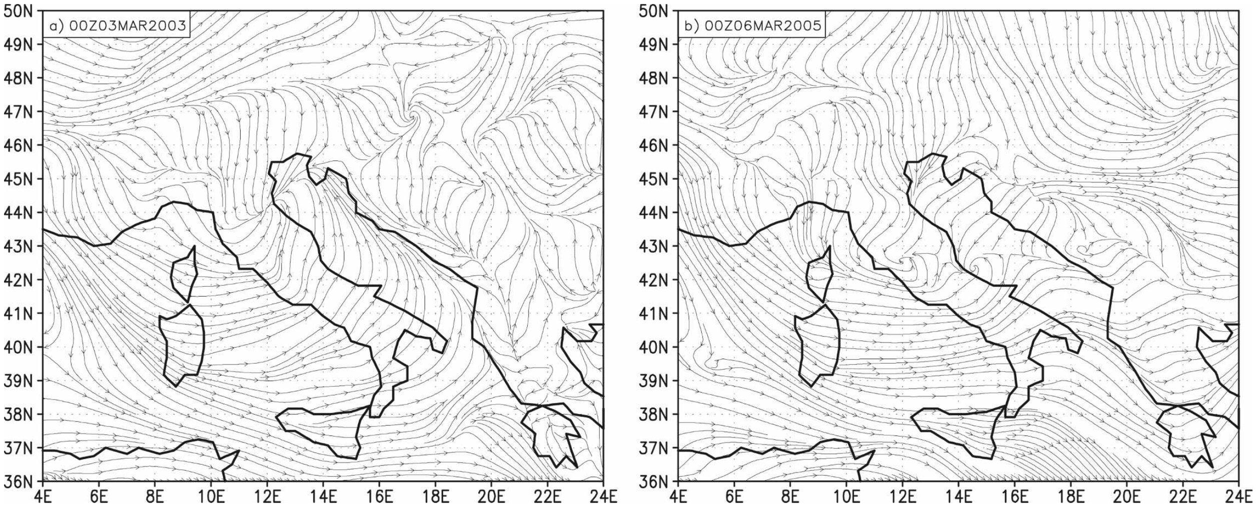

FIG. 8. Streamlines of the (a) continuous (0000 UTC 3 Mar 2003) and (b) discontinuous (0000 UTC 6 Mar 2005) Genoa cyclones (see Figs. 6 and 7) at the moment the cyclones traversed the Apennine peninsula. Discontinuous cyclones, besides having separate MSLP centers, also have two separate vorticity centers.

March 2005, the cyclone moved over to the Tyrrhenian Sea, following the well-known Genoa cyclone track along the western Italian coast. However, instead of taking the usual path to the Ionian Sea without crossing the Apennines, the cyclone traversed the middle Apennines to the Adriatic Basin. In addition to the steering from the upper-level flow mentioned earlier, convection over the middle Apennines might also contribute to cyclone track deflection to the east. While the cyclone was traversing the mountain range, two separate cyclone centers were detected (Figs. 7c,d). In contrast to the type A-I cyclone that kept its continuity over the peninsula (Fig. 8a), both centers of this cyclone had a closed 2-hPa isobar and separate vorticity cores (Fig. 8b) on both sides of the peninsula, present at the same time and separated by the mountain range. In subsequent hours, the windward center experienced a cyclolysis, while the lee center continued the life cycle. Finally, the cyclone moved over the Adriatic Sea and impinged on the southern part of Croatian Dinaric Alps, while a new system was already generating in the Gulf of Genoa (Figs. 7e,f). This type of analyzed cyclone often results in a cyclonic bora and severe weather conditions along the middle and southern Dinaric Alps, while there is a lack of strong bora in the northern Adriatic, which is the area where bora duration and frequency reach the climatological maximum.

b. *Type B—Adriatic cyclones*

The analyzed B-I northern Adriatic cyclone was generated on 4 November 2002 (Figs. 9a,b). The upper-level trough started to traverse the Alps on 1800 UTC 3 November. The trough penetrated southwestward with a more gradual positive axis tilt (i.e., shifting from northwest–southeast to northeast–southwest). At lower levels, seasonal and nighttime thermal effects created a mesoscale thermal anomaly over the Adriatic Sea, while westerly and northwesterly flow dominated the Alpine region. Blocking and stagnation took place on the west–northwest (windward) side of the Alps. The southern branch entered the Mediterranean, causing a weak thermal effect and an associated thermal anomaly in the Gulf of Genoa. The northern branch of the airflow partly circumvented and partly crossed the Alps, creating a moderate cold air outbreak in the Dinaric (eastern) Alps region. Therefore, both dynamical and thermal effects seem to contribute to the created low-level thermal anomaly in the northern Adriatic area. Upon generation, the subsequent cyclone movement (Figs. 9c,d) resembles the type A-I cyclones described above. In general, it appears that to a certain extent, B-I cyclogenesis and deepening dynamics follow the essential principles of the Alpine lee cyclones (e.g., Aebischer and Schär 1998). Accordingly, the weather conditions and the related chain of events involving the local bora and *jugo* winds during the cyclone movement along the basin resemble the ones of Genoa cyclone (discussed above).

A typical B-II middle Adriatic cyclone has the smallest scale among different types of cyclones in the region. Because of its dimensions and weak intensity (the cyclone discussed below is one of the most intense detected), this type of cyclone is not associated with severe weather. Nevertheless, the seasonal distribution of

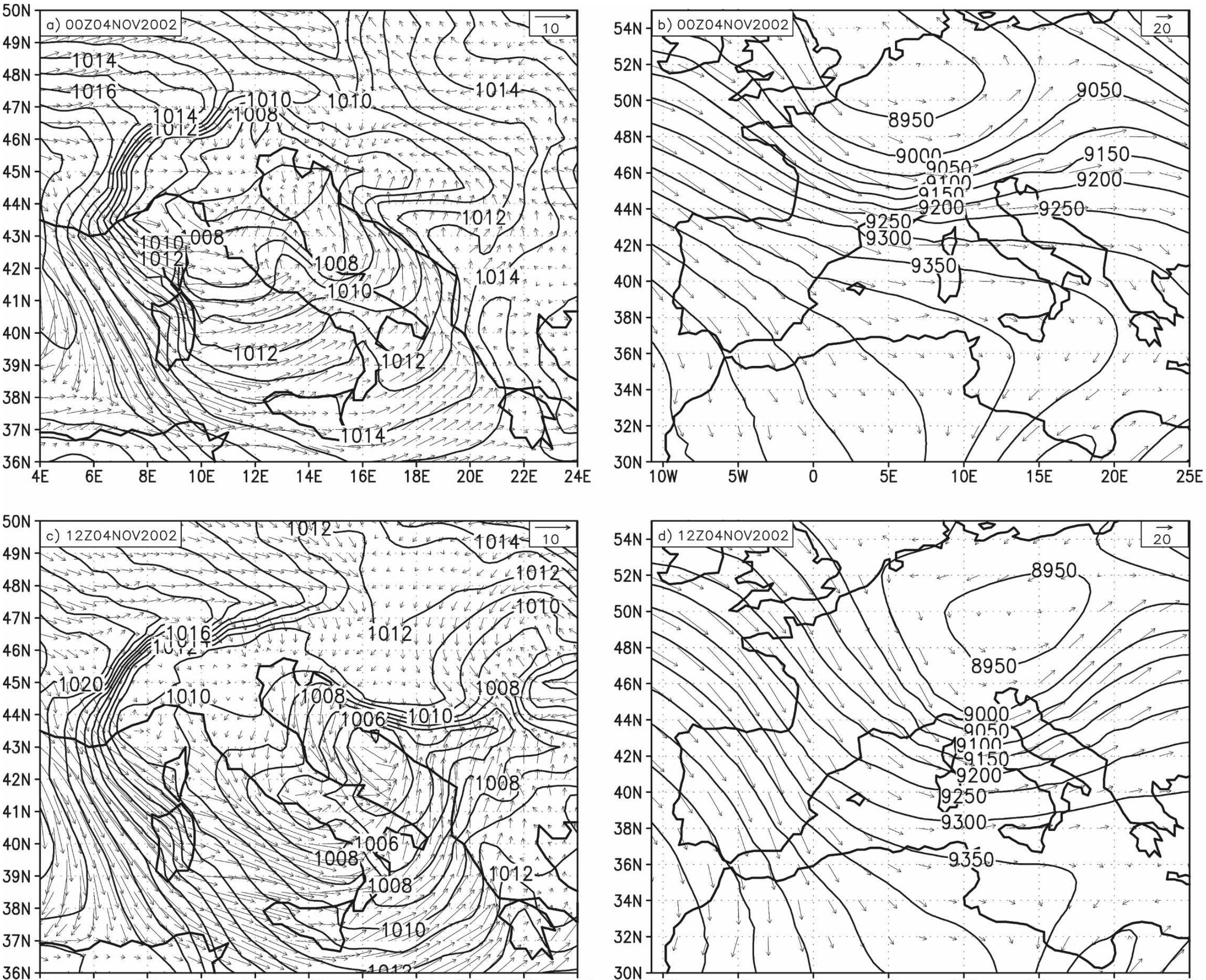

FIG. 9. A northern Adriatic cyclone (type B-I) (left) surface MSLP and wind fields and (right) geopotential and wind fields at 300 hPa on (a),(b) 0000 UTC 4 Nov 2002 and (c),(d) 1200 UTC 4 Nov 2002.

these cyclones has a peak in summer, when these cyclones can cause high-impact weather, especially in the case of poor forecasts. The case shown was related to summer storms that produced ~30 mm in 12 h on the southern Adriatic islands, where weather conditions are normally characterized by mild, fair, and very dry weather in summer.

At the upper levels, a mesoshortwave trough propagated eastward over the northern Mediterranean, with no surface cold front associated. At 1800 UTC 24 July, the trough reached the middle Apennine mountain range (Figs. 10a,b). In subsequent hours, a well-localized cyclone formed in the lee of the mountain. The cyclone quickly traversed the Adriatic Sea and deepened to its maximum intensity. Preliminary numerical analysis indicates that the surrounding mountains acted as scale contractors and confined the cyclone size to one comparable to those in the Adriatic Basin. Upon reaching the eastern Adriatic coast, the surface cyclone was blocked by the Dinaric Alps and the system shifted from upshear to downshear tilt (Figs. 10c,d). A subsequent decoupling of the system was not associated with the immediate cyclolysis; instead, it appears that the heat fluxes from the sea might have served as a source of energy for further cyclone life cycle maintenance. In addition, both convergence of the local bora and *jugo* winds and conditional instability of the second kind were proposed as additional cyclone deepening mechanisms (Ivančan-Picek 1998).

Overall, the mechanism of cyclone initiation seems to be similar to that of lee cyclogenesis. However, the scales of the motion, which are controlled by different ingredients of cyclone formation and deepening, are much smaller than in well-investigated cases of typical

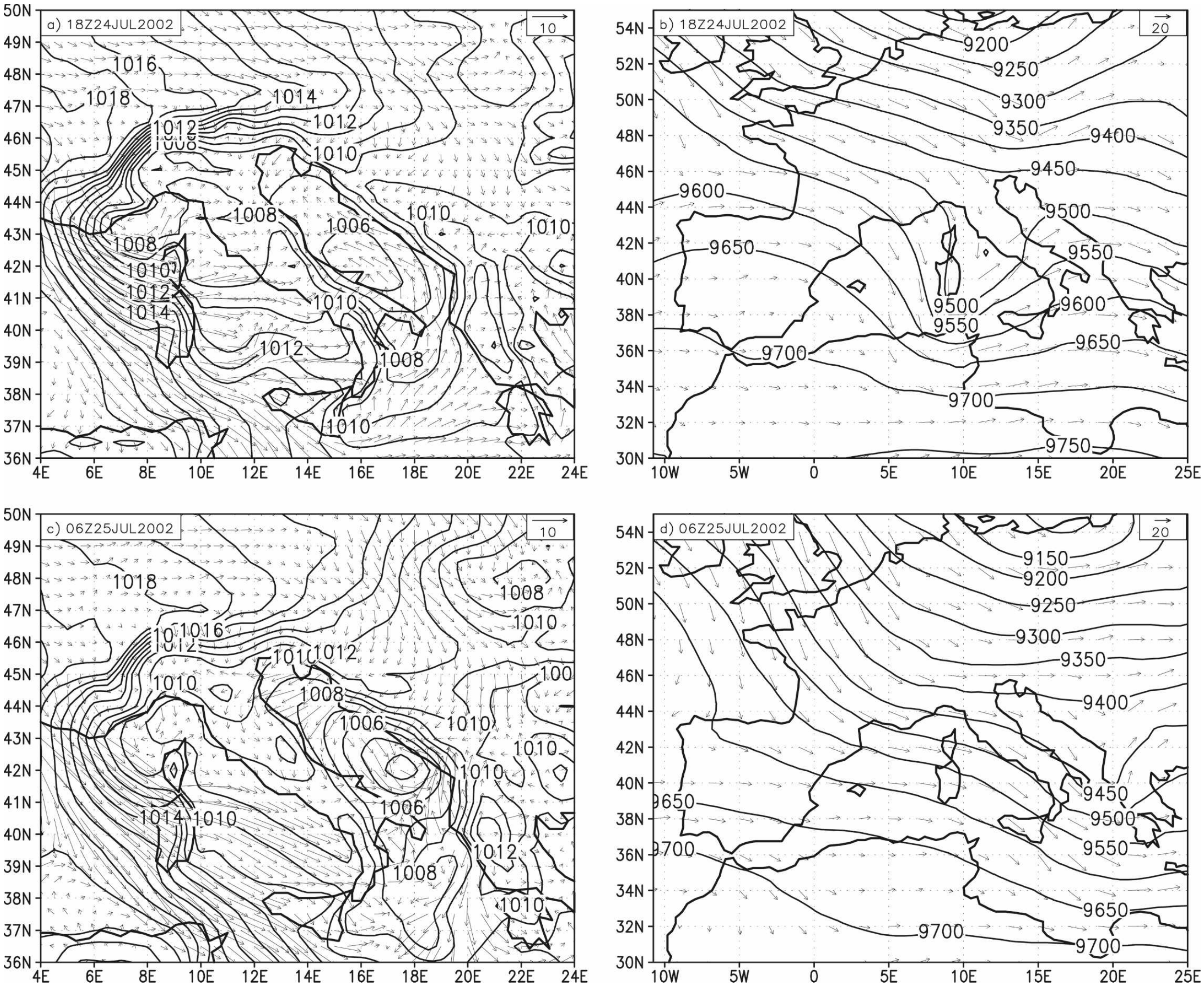

FIG. 10. A middle Adriatic cyclone (type B-II) (left) surface MSLP and wind fields and geopotential and wind fields at 300 hPa on (a),(b) 1800 UTC 24 Jul 2002 and (c),(d) 0600 UTC 25 Jul 2002.

examples of orographical cyclogenesis (e.g., Alps, Rocky Mountains).

c. Type AB—“Twin” cyclones

The twin or eyeglass AB type of cyclone was associated with advection of a wide trough over the broad Alpine area on 1800 UTC 13 Feb 2005 (Figs. 11a,b). At this time, two lows were simultaneously present in the Gulf of Genoa and the northern Adriatic. Concurrently, a fast-moving potential vorticity streamer started to cross the Alps. The axis of this elongated geopotential trough was directed west-southwest–east-northeast, with both Genoa Bay and the northern Adriatic on the front side of the streamer at the same time. In subsequent hours, the Genoa low evolved into a fast-moving cyclone, while the northern Adriatic low advected along the Adriatic Basin and merged with the cyclonic system in the lee of the middle Apennines (Figs. 11c,d). The time resolution of the analysis does not allow us to examine the details of this merge, but the middle Apennines appear to be the main contributor to the initial phase of the middle Apennine system creation (0000 UTC, not shown). However, a numerical analysis of a twin cyclone case (Brzović 1999) indicates that the Adriatic twin is a consequence of the influence of the Dinaric Alps on the northeasterly flow; that is, this twin is a lee cyclone with respect to the Dinaric Alps. However, because of the insufficient number of studies, it is not completely clear to what extent this conclusion is case dependent. Further on in the life cycle, the Genoa twin moved down the western Italian

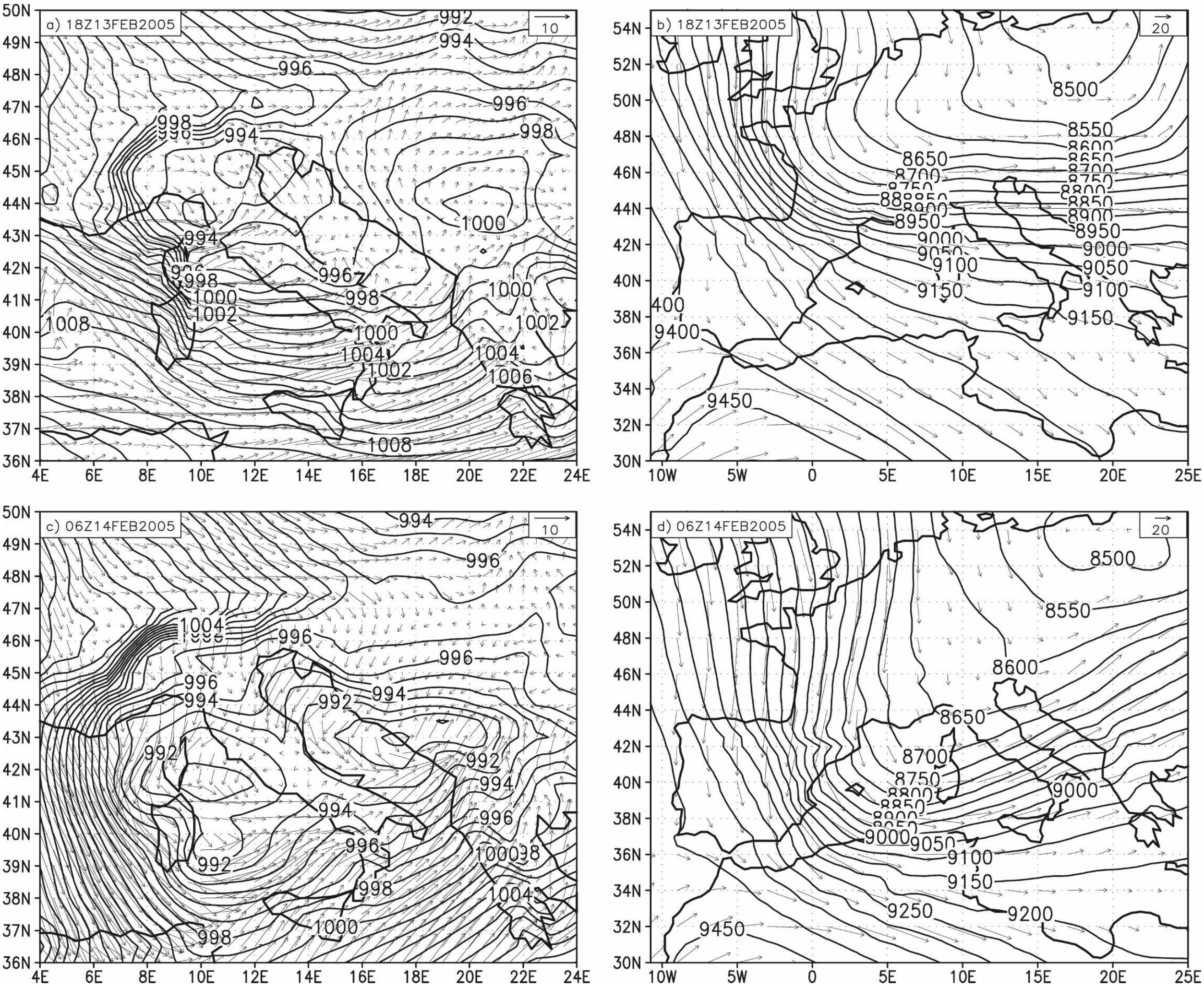

FIG. 11. A twin/eyeglass cyclone (Type AB) surface MSLP and wind fields (left) and (right) geopotential and wind fields at 300 hPa (right) on (a),(b) 1800 UTC 13 Feb 2005 and (c),(d) 0600 UTC 14 Feb 2005.

coast, steered by the upper-level streamer, while mature Adriatic twin traversed the Dinaric Alps to the east.

d. Common characteristics

Note that a common feature of all the typical cyclone types initiated in the region is an upper-level trough. This is in accordance with the ALPEX study (Pichler and Steinacker 1987) in which the authors analyzed 40 events of Alpine lee cyclogenesis that emerged during the 13 months of the experiment. Among the results, it was evidenced that an upstream upper-level vorticity maximum was a necessary ingredient of Alpine lee cyclogenesis. This finding, together with the preferred genesis locations of type A and B cyclones, might imply that lee cyclogenesis is the dominant formation process in the region for all the cyclone types identified. However, there are significant differences in dimensions of the upper-level troughs for all the types detected, ranging from almost meso-β (for type B-II) to macroscales (types A and C). Similarly, a small-scale vorticity core embedded in a broader-scale upper-level disturbance appears to be the key process in some occasions. Moreover, it remains to be further investigated what the role of low- and upper-level vortex interaction in the Apennine lee cyclogenesis may be, considering the meso-β scale of the cyclone and the lack of strong and characteristic cold air blocking. This implies that at least the B-II formation process might be the result of a more complex interaction. To support conclusions of this type, numerical analysis and factor separation methods will be performed in the forthcoming experiments.

5. Conclusions and final remarks

Operational analyses of the ECMWF on a T511 spectral resolution were subjectively analyzed throughout a 4-yr period in order to evaluate the cyclone activity over the Adriatic Sea. The detection and tracking procedure included objective MSLP and cyclone duration thresholds and a subjective vorticity analysis, with closed circulation as a guidance criterion.

Cyclone types identified include cyclones that initiated in the Gulf of Genoa (type A), in the Adriatic (type B), in both Genoa and the Adriatic simultaneously (type AB), and elsewhere (type C). In addition, cyclones that traversed the Apennine peninsula were classified based on their continuity on the Apennine range (for types A and C). The inclusion of discontinuous cyclone types is a specific necessity of the cyclone climatology classification in the Adriatic area, where a great majority of cyclones cross the Apennine mountain range on their way to the region.

Cyclones initiating in the Gulf of Genoa or northern Italy (type A) constitute more than 35% of the cyclones that enter the Adriatic Basin and most often occur in the winter. This type of cyclone usually traverses the northern Adriatic through northern Italy and the Po Valley, without a significant disturbance of vorticity patterns above the peninsula (type A-I). Once in the northern Adriatic, the cyclone tracks diverge: while most cyclones follow the main path down the basin, a few follow the secondary tracks and cross the northern Dinaric Alps, advecting either eastward or northeastward. In addition, some Genoa cyclones slide along the western Italian coast to the Tyrrhenian Sea and traverse the middle Apennines on the way to the Adriatic. Because of the height of the middle Apennines range (2912 m), a subset of these cyclones becomes discontinuous over the mountain (type A-II). This process is accompanied by the presence of two simultaneous cyclone centers on the upstream and downstream parts of the mountain.

Type A cyclones cause a chain of related weather conditions on the eastern Adriatic coast, where strong *jugo-* and mountain-induced precipitation (on the western slopes of the Dinaric Alps) precede strong bora winds that start at the northern Adriatic and gradually spread toward the southern Adriatic as the cyclone moves down the basin. These cyclones are moderately well predicted, although both predictions of bora wind speed and gustiness and site-specific precipitation forecasts are sometimes notably poor over the eastern Adriatic coast on account of erroneous forecasting of the exact cyclone location.

Adriatic cyclones (type B) are the smallest-scale cyclones analyzed, often with horizontal dimensions of the basin width (200 km). These cyclones are initiated in localized areas of the northern Adriatic (B-I) and western part of the middle Adriatic (B-II) and constitute 25% of the total number of cyclones detected in the basin. Type B-I cyclones typically initiate in the northern Adriatic and move southeast over the basin. The initiation process of this type of cyclone seems to be qualitatively similar to the Genoa lee cyclogenesis process. These cyclones form mostly in the cold part of the year and can deepen considerably. Type B-II initiates in the lee of the middle Apennines and quickly traverses the Adriatic Sea perpendicular to the main axis. The cyclones tend to form more often in the warmer part of the year and usually do not deepen more than 4–5 hPa in the Adriatic area. This type of rather shallow cyclone often gets blocked by the Dinaric Alps and decoupled from the shortwave upper-level disturbance simultaneously. As a whole, the northern and the middle Adriatic regions have similar frequency of cyclone appearances. While the weather conditions of type B-I cyclones are similar to those of type A cyclones, B-II cyclones cause high-impact weather (e.g., summer storms) only in summer (when their seasonal distribution has a maximum) because of their shallowness. However, probably on account of their scale and weak intensity, these cyclones are the least predictable of all cyclone types identified in the study. Therefore, knowledge about their climatology and physical mechanisms might have a potential use in everyday operational forecast practice.

Another type of cyclone initiated in the region is the twin or eyeglass cyclone type (type AB). These cyclones are characterized by the simultaneous presence and evolution of two cyclones, one in the Adriatic and one in the Gulf of Genoa. This rather rare type of cyclone usually slides down along the western and eastern part the Apennine peninsula, and occasionally an Adriatic twin member crosses the Dinaric Alps to the east.

Type C cyclones have initiation areas other than Genoa or the Adriatic and constitute 35% of the total number of cyclones that are detected in the Adriatic. The migration areas include the Atlantic Ocean, the Atlas Mountains, the Pyrenees, the Iberian Peninsula, the Alboran Sea, and others. Because of their dimension and remote locations of initiation, these cyclones and the weather associated with them (which is highly dependent on the location of the cyclone entrance in the Adriatic Basin) are usually well forecast. These cyclones occur most often in winter and the least during the summer. Since the main summer cyclogenetic area is the Iberian Peninsula, it is noteworthy that their tracks diminish as they approach the Genoa Bay and the Adriatic along their northeastward track (Trigo et al. 1999). This seems to be a consequence of the lack of upper-level forcing and the existence of predominant etesian circulation that disable the farther cyclone northeastward protrusion to the Adriatic. In addition, type C cyclones occasionally experience a chain-like series of redevelopments along the Mediterranean. This amplifies the complexity of the analysis and might longitudinally increase the uncertainty of the Mediterranean cyclone climatology.

Generation mechanisms of Genoa and Adriatic cyclones are inherently associated with an advecting upper-level trough over the mountain lee area and the associated cold air blocking and creation of thermal anomalies, which are a predominant ingredient of the first phase of the lee cyclogenesis. Additionally, it seems that the effect of sea heat fluxes and the associated heat capacities of the regional geomorphologic elements might have an effect in creating the thermal anomalies over the almost completely mountain-enclosed Adriatic Basin. In general, these two processes result in a high frequency of thermal anomalies over the basin. Regardless of the possibly differing formation mechanisms, the presence of thermal anomalies and upper-level troughs seem to imply a certain similarity between Adriatic and Alpine cyclogenesis. In addition, heat fluxes and the convergence of the local *bura* and *jugo* winds might contribute to cyclone deepening over the Adriatic Sea. However, only a numerical analysis of cyclone properties can elucidate the formation and deepening mechanisms of the discussed cyclone types in the region in more detail.

This study could not avoid uncertainties due to the length of the analyzed period. For example, the period of 2002–05 was one of the warmest 4-yr periods since the onset of conventional measurements. Further, the increased meridional Mediterranean cyclone movement in 2002, together with flood-causing Mediterranean cyclones in the Czech Republic, the failure of the Asian monsoon (which is related to ENSO), and large-scale circulation patterns in the Mediterranean (see, e.g., Webster and Yang 1992), seems to imply that that year was characterized by an anomalous macroscale flow circulation pattern. Such circumstances might result in deviations from the long-term cyclone climatology if the analyzed period is not sufficiently long.

In future work, this climatology study and the presented cases will serve as a platform for the analysis of precipitation patterns of different cyclone tracks in the Adriatic and as a background for numerical modeling and analysis, and will be a tool for understanding the dynamical and physical properties of the Adriatic cyclones.

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