P3M.11 INFLUENCE OF THE APENNINES AND OTHER FACTORS ON GENOA CYCLONE MOVEMENT DURING MAP

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1. INTRODUCTION

Two mesoscale cyclones were observed during the Mesoscale Alpine Programme (MAP), which exhibited dramatically different track characteristics as they pass over the Apennines, a mountain chain with an average height of about 1000 m spanning along the length of the Italian peninsula. These cyclones occurred during IOP-1 and IOP-8. They formed near the Gulf of Genoa, propagated eastward, and approached the Apennines. For IOP-8, the surface cyclone slowed down along the upstream (west) side of the mountain and accelerated over the mountain range, but appeared to be slightly deflected towards the south and became discontinuous as it crossed the Apennines. This led to the formation of a secondary low in the lee of the Apennines that developed into the dominant surface cyclone. For IOP-1, the surface cyclone appeared to be deflected towards the south as it approached the upstream side of the Apennines, remaining on the western side of the mountain range until reaching the southern end of Italy. This study will investigate the factors that led to the different tracks of these two cyclones.

Lin et al. (2005) found that the tendency for tropical cyclones passing over the Central Mountain Range in Taiwan to be deflected was dependent on two control parameters: the vortex Froude number, which is given by

$$F_{vor} = V_{max}/Nh \qquad (1)$$

and the basic flow Froude number, given by

$$F = U/Nh \qquad (2)$$

where U is the basic flow speed, V_{max} is the maximum tangential wind speed of the cyclone, N is the Brunt-Väisäla frequency upstream of the orography, and h is the mountain height. In this paper, we will examine to what extent these two control parameters dictate whether the MAP IOP-1 and IOP-8 Genoa cyclones are deflected as they approach the Apennines. We will also look at factors that may have influenced the track differences between the IOP-1 and IOP-8 Genoa cyclones, such as orographic blocking by the Apennines, interaction with the mountains of Corsica, effects of friction and synoptic forcing.

2. CYCLONE ENVIRONMENTS

The IOP-8 Genoa cyclone initially developed between 00 and 06 UTC 21 October 1999. Figure 1 shows sea-level pressure and surface winds from 18 UTC 21 October 1999 (10/21/18Z) to 10/22/18Z. These analyses are based on the ECMWF 0.5º reanalysis data. At 10/21/06Z, the cyclone developed just off the southeast coast of France (not shown). During the following 12 h, the cyclone approached Corsica and appeared to develop a secondary cyclone on the lee of Corsica. By 10/21/18Z (Fig. 1a), the secondary cyclone (marked as L2 in Fig. 1a) continued to move towards the west of the coast of Italy. During the next 12 h, the cyclone approached the Apennines and another secondary cyclone (marked as L3 in Fig. 1b) developed in the lee of the Apennines, as seen at 10/22/06Z (Fig. 1b). The L3 cyclone phased with the upper-level low and became the dominant surface cyclone while the L2 cyclone dissipated along the western side of the Apennines (Fig. 1c). A more complete assessment of the cyclone track can be gained through inspection of Fig. 2 which shows the cyclone position at the surface, 500 hPa and 300 hPa. The surface cyclone track shows that at 10/22/06Z there were two cyclones present on either side of the Apennines. For IOP-8, the cyclone track was generally oriented west to east.

The surface cyclone for IOP-1 developed between 09/15/06Z and 09/15/12Z. The sea-level pressure and surface winds for IOP-1 are shown in Fig. 3. Figure 3a shows that at 09/15/18Z, the secondary cyclone developed to the lee of Corsica (marked at L1). At 09/16/00Z (Fig. 3b), the

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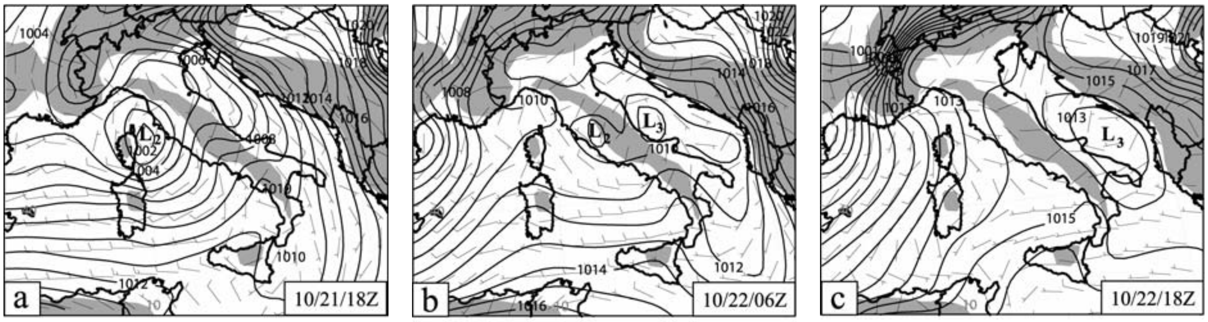

Figure 1: Sea level pressure (solid contours) and surface winds for IOP-8.

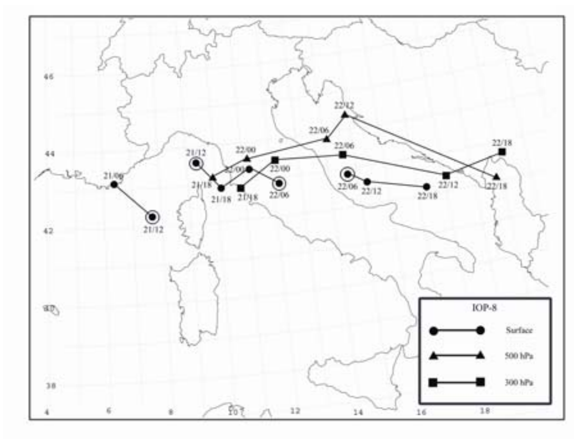

Figure 2: Cyclone track for IOP-8 at the surface, 500, and 300 hPa (see legend in figure).

surface cyclone interacted with Corsica and a secondary cyclone developed in the lee of Corsica (marked as L2). By 09/16/12Z (Fig. 3c), the cyclone had moved past Corsica and was just west of the Italian coastline. Rather than continue eastward over the Apennines, the Genoa cyclone appeared to be deflected towards the southeast during the following 24 h (not shown). The cyclone tracks at the surface, 500 hPa and 300 hPa are shown in Fig. 4. This figure shows the track for the surface cyclone had a strong southerly component, unlike that for IOP-8 (Fig. 2). This figure also shows that the surface cyclone for IOP-1 experienced a discontinuous track while crossing the mountains of Corsica.

Based on the ECMWF reanalysis data, the vortex Froude number and basic flow Froude number were calculated using the V_{max}, U, N, and h listed in Table 1. Since both cyclones encountered Corsica, the values in the table were estimated at times before and after the surface cyclone interacted with Corsica. For the height of the Apennines, we estimated the average value of h = 1000 m. The value of N was calculated by using the temperatures from the 1000-800 hPa layer in soundings taken just upstream of the Apennines. The value of the basic flow speed, U, was estimated by taking the 12 h average of the 700 hPa wind speed above the cyclone location. The V_{max} value associated with the IOP-1 and IOP-8 Genoa cyclones was estimated by taking the average surface wind speeds on the western and eastern sides of the cyclone, to discount the effect of forward motion on the value of V_{max}. Given those estimated values, IOP-1 had V_{max}/Nh values of 0.63 and 0.42 which are very small compared to the minimum V_{max}/Nh necessary for non-deflected cyclone tracks noted in Lin et al. (2005). The V_{max}/Nh values for IOP-8 were 1.36 and 0.91 which are relatively large compared to the minimum V_{max}/Nh necessary for non-deflected tracks. The U/Nh values were also larger for the IOP-8 cyclone compared to the IOP-1 cyclone. It is hypothesized that those larger values of V_{max}/Nh and U/Nh are an indication of less track deflection for the IOP-8 Genoa cyclone as it approached the Apennines, as is the case with tropical cyclones crossing mesoscale terrain. In order to examine the extent that those control parameters dictated the deflection of the IOP-1 and IOP-8 Genoa cyclones as they approached the Apennines, numerical sensitivity experiments have been performed.

3. EXPERIMENT DESIGN

Numerical simulations were performed by using the Penn State/NCAR MM5 model. Two nested domains, with two-way interaction, were used for the simulations. Domain 1 used a 45-km grid spacing with 91x85 grid points in the horizontal, and domain 2 used a 15-km grid spacing with 121x121 grid points. Forty-five unevenly spaced full-sigma levels were used in the vertical with the maximum resolution in the boundary layer. The time steps for domains 1 and 2 were 90s and 30s, respectively. The ECMWF ERA40 2.5º x 2.5º reanalysis data was used to initialize the model and update the boundary conditions every six

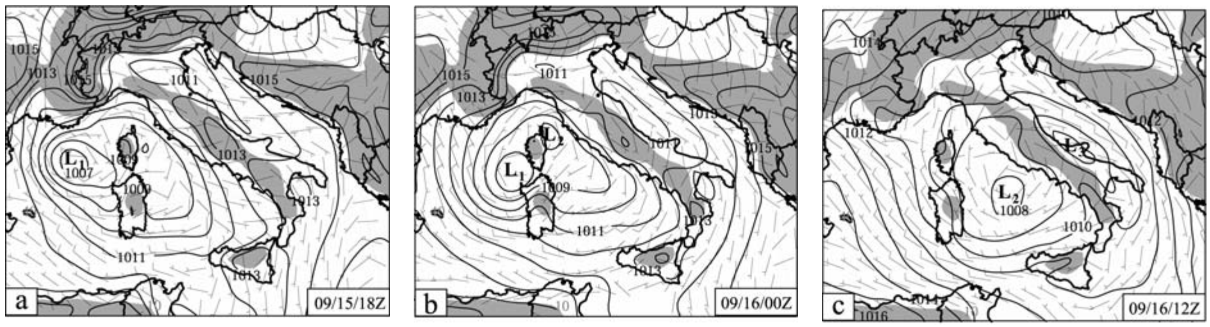

Figure 3: Sea level pressure (solid contours) and surface winds for IOP-1.

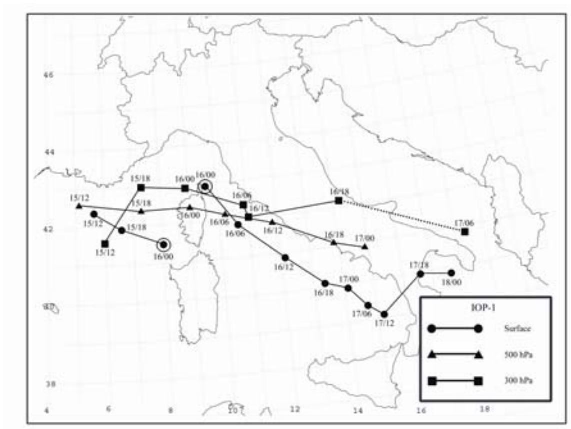

Figure 4: Cyclone track for IOP-1 at the surface, 500, and 300 hPa (see legend in figure).

hours. The IOP-8 experiments were initialized at 10/17/00Z while the IOP-1 experiments were initialized at 09/14/00Z. The control simulations performed for this case agreed relatively well with the observations and reanalysis data on the development and tracks of the IOP-1 and IOP-8 of the Genoa cyclones (not shown).

4. EXAMINATION OF CONTROL PARAMETERS

As was discussed in section 2, for the purpose of our study we will be examining how well the control parameters V_{max}/Nh and U/Nh can dictate the track deflection of the IOP-1 and IOP-8 Genoa cyclones. As before, we will use h = 1000 m. The value of N was again calculated by using the temperatures from the 1000-800 hPa layer in a sounding taken just upstream of the Apennines for the IOP-1 control simulation (CTRL1) and the IOP-8 control simulation (CTRL8). For CTRL1, N = .010 s^{-1}, and for CTRL8, N = .012 s^{-1}. The value of the basic flow speed was estimated as U = 10 m s^{-1} for CTRL1 and U = 13.3 m s^{-1} for CTRL8. Those values are slightly faster than the reanalysis data, but still comparable. For the CTRL8, the cyclone remained north of Corsica throughout the simulation, but became slightly disorganized as it crossed through the Ligurian Sea, thus the V_{max} value of 10 m s^{-1} was obtained shortly after the cyclone had developed at 10/21/12Z. The CTRL1 V_{max} value of 10 m s^{-1} was determined shortly after it had crossed into the Tyrrhenian Sea at 09/16/06Z since that time provided the best circular flow to perform the wind speed average. This CTRL1 V_{max} value is slightly larger than that obtained using the reanalysis data, a difference that can be attributed to the CTRL1 cyclone being somewhat more organized and deeper as it crossed the Tyrrhenian Sea than in the reanalysis data. These estimated values for h, N, U, and V_{max} are listed in Table 2, along with the calculations of V_{max}/Nh and U/Nh. For CTRL1, V_{max}/Nh = 1.00, while V_{max}/Nh = 0.83 for CTRL8.

According to Lin et al. (2005), track deflection increases with decreasing F_{vor}. Yet, CTRL1, which appears to exhibit a greater degree of deflection, has a larger F_{vor}. Such a result may indicate that F_{vor} may not act as a control parameter for surface cyclone movement in these cases. In the case of CTRL1 and CTRL8, however, CTRL1 has the larger value of V_{max}/Nh and yet CTRL1 was the cyclone that experienced the greater southward deflection. Based on this result, it appears that the maximum tangential wind speed of the cyclone (V_{max}) did not play a role in the degree of deflection that the IOP-1 and IOP-8 Genoa cyclones experienced as they approached the Apennines.

Based on the values simulated by the MM5, U/Nh = 1.00 for CTRL1 while U/Nh = 1.11 for CTRL8. Lin et al. (2005) found that the track deflection of the tropical cyclone track will be greater given smaller values of U/Nh. Since the CTRL1 value is smaller than the CTRL8 value, it appears as though the basic flow of the system may be a possible determining factor for the degree of track deflection. To test this hypothesis, simulations identical to CTRL1 and CTRL8 were performed wherein the Apennines were removed.

Table 1: Flow and orographic parameters estimated with ECMWF reanalysis data for IOP-1 and IOP-8, where *U* is the basic wind speed, *Vmax* is the maximum tangential wind speed of the vortex, *N* is the Brunt-Väisäla frequency, and *h* is the average height of the Apennines.

Case	*U*	*Vmax*	*N*	*h*	*Vmax/Nh*	*U/Nh*
	(ms^{-1})	(ms^{-1})	(s^{-1})	(*m*)		
IOP-1: 09/15/18Z	15.0	7.5	.012	1000	0.63	1.25
IOP-1: 09/16/12Z	10.0	5.0	.012	1000	0.42	0.83
IOP-8: 10/21/06Z	18.3	15.0	.011	1000	1.36	1.66
IOP-8: 10/21/18Z	16.6	10.0	.011	1000	0.91	1.51

Table 2: Flow and orographic parameters estimated with MM5 model data for IOP-1 and IOP-8.

Case	*U*	*Vmax*	*N*	*h*	*Vmax/Nh*	*U/Nh*
	(ms^{-1})	(ms^{-1})	(s^{-1})	(*m*)		
CTRL1: 09/16/06Z	10.0	10.0	.010	1000	1.00	1.00
CTRL8: 10/21/12Z	13.3	10.0	.012	1000	0.83	1.11

These simulations are referred to as the NOAP1 and NOAP8 simulations, respectively. This set the value of *U/Nh* equal to infinity. Thus, if *U/Nh* is indeed a control parameter for determining the degree of track deflection for the IOP-1 and IOP-8 Genoa cyclones, then both cyclones should exhibit little or no deflection as they cross the Italian peninsula.

Figure 5 shows the track plots of the NOAP8 cyclone circulation centers at the surface, 500 hPa and 300 hPa from 10/21/12Z to 10/22/12Z. The NOAP8 surface cyclone developed a similar time and location as that in the CTRL8 simulation. By 10/21/18Z, the NOAP8 surface cyclone had followed an eastward track toward the western coast of Italy. Upon reaching the flat terrain of Italy, the NOAP8 surface cyclone proceeded to cross Italy continuously with only a slight deflection towards the north. As had been hypothesized, the NOAP8 surface cyclone experienced little deflection as it crossed Italy without the presence of the Apennines.

Figure 6 shows the track plots of the NOAP1 cyclone circulation centers at the surface, 500 hPa and 300 hPa from 09/15/18Z to 09/18/06Z. Without the Apennines, the NOAP1 surface cyclone approached the west coast of Italy in a relatively eastward direction up through 09/16/12Z. However, at 09/16/18Z, the NOAP1 surface cyclone began moving toward the southeast along the west coast of Italy, eventually crossing Italy around its southern tip. This southward deflection goes against the hypothesis that the NOAP1 surface cyclone should have been able to cross over Italy without the presence of the Apennines. Recall that since the Apennines are not present in

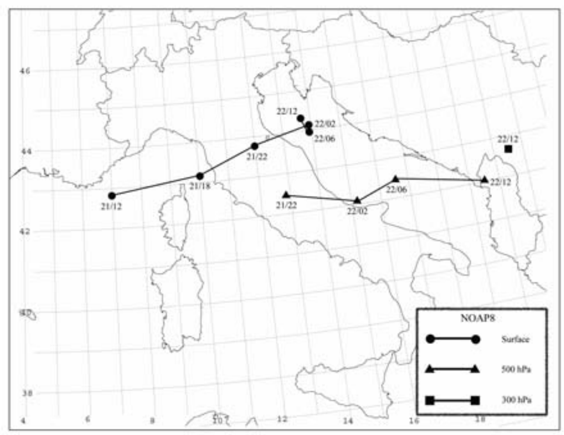

Figure 5: Cyclone track for NOAP8 at the surface, 500, and 300 hPa (see legend in figure).

either the NOAP8 or NOAP1 simulations, the value of *F* is infinity. Despite this, the NOAP1 surface cyclone experienced an apparent southward deflection as in the CTRL1 simulation. This indicates that the southward movement of the IOP-1 surface cyclone was not due to mountain deflection. Yet, we do note that in the NOAP8 simulation, the degree of surface deflection was reduced as compared to the CTRL8 simulation. Hence, we can conclude that the flow parameters F_{vor} and *F* may not always serve as indicators of track deflection.

Since the NOAP1 surface cyclone still deflected towards the south without the presence of the Apennines over Italy, it appears that orographic blocking did not play a role in this southeastward track of the IOP-1 cyclone. This is contrary to the findings of Lin et al. (2005) in which

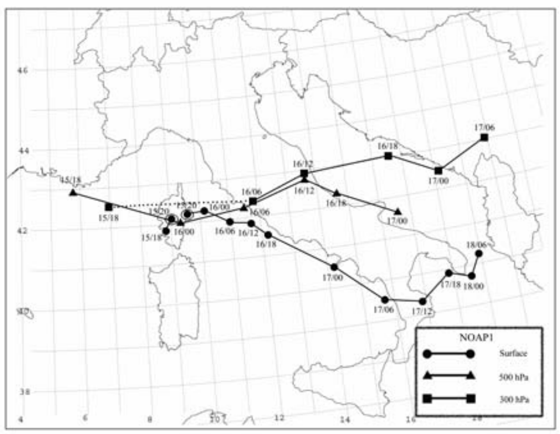

Figure 6: Cyclone track for NOAP1 at the surface, 500, and 300 hPa (see legend in figure).

they found that tropical cyclone track deflection was controlled by orographic blocking. As a result, it appears that the IOP-1 cyclone track is not really a case of track deflection, but rather a case of cyclone movement. With that being the case, it raises the question, “What did lead to the southeastward movement of the IOP-1 Genoa cyclone?” In the following section, we will use the CTRL1 and CTRL8 simulated results along with further numerical experiments to examine various factors such as the influence of the mountains of Corsica, the effects of friction and synoptic forcing to determine what role, if any, they played in influencing the track of the IOP-1 Genoa cyclone.

5. EXAMINATION OF POSSIBLE FACTORS INFLUENCING CYCLONE MOVEMENT

Even though the Apennines did not appear to influence the track of the CTRL1 surface cyclone, that cyclone did cross Corsica before approaching the Apennines. Therefore, it is possible that the interaction of the surface cyclone with the mountains of Corsica may have influenced the southeastward movement of the cyclone. To examine this hypothesis, a simulation was performed in which the terrain of Corsica was removed (NOCO1) (not shown) while keeping everything else identical to the CTRL1 simulation. Without the presence of Corsica, the NOCO1 surface cyclone easily crossed over Corsica and moved into the Tyrrhenian Sea. However, at 09/16/06Z, the NOCO1 surface cyclone essentially stalled over the Tyrrhenian Sea, having barely moved within the previous 6 h and, by 09/16/12Z, the surface cyclone was once again on a track towards the southeast. Therefore, the encounter with the mountains of Corsica did not appear to influence the southeastward movement of the CTRL1 surface cyclone.

Instead of the mountains of Corsica influencing the movement of the CTRL1 surface cyclone, it appears as though something along the west coast of Italy may have affected the CTRL1 surface cyclone which led to the eventual southeastward movement. A possible reason could be due to frictional effects between the coast of western Italy and the Tyrrhenian Sea. To test this hypothesis, a numerical simulation was performed in which the effects of friction were suppressed by turning off the surface fluxes within the boundary layer scheme (NOFR1) (not shown), while keeping everything else identical to the CTRL1 simulation. The NOFR1 surface cyclone developed and progressed towards the east in a similar manner to the CTRL1 cyclone. After moving into the Tyrrhenian Sea at 09/16/06Z, the NOFR1 surface cyclone stalled in its eastward progression, as had been seen within the NOCO1 simulation. By 09/16/12Z, the NOFR1 surface cyclone was headed towards the southeast along the western side of Italy. Since the NOFR1 surface cyclone was not able to cross over the Apennines, it appears as though frictional effects were not responsible for influencing the movement of the CTRL1 surface cyclone.

Genoa cyclones develop within the mid-latitude region where there is greater baroclinicity compared to the tropics. Thus, the synoptic flow may have had a greater influence on the tracks of the IOP-1 and IOP-8 Genoa cyclones compared to its effect on tropical cyclones. For the CTRL8 simulation, a comparison between the location of the trough axis in the 300 hPa geopotential heights (not shown) and that of the dominant surface cyclone within the sea-level pressure analyses indicates that the dominant surface cyclone remained just downstream of the upper-level trough axis throughout the passage of the surface cyclone across the Apennines and into the Adriatic Sea. As a result, upper-level westerly or southwesterly flow was constantly present above the dominant CTRL8 surface cyclone. This vertical alignment of the westerly flow aloft may have helped with the eastward propagation of the CTRL8 surface cyclone across the Apennines. A comparison between the CTRL1 plots of sea-level pressure and the 300 hPa geopotential heights and winds (not shown) indicates that the surface cyclone also remained just downstream of the 300 hPa closed low and trough axis, as had been the case with the CTRL8 cyclone through 09/16/00Z. However, by 09/16/12Z, the 300 hPa closed low was positioned well over central Italy while the surface cyclone remained over the Tyrrhenian Sea, just to the east of Corsica. A further examination of the CTRL1 300 hPa geopotential heights and winds shows that a ridge over the Adriatic Sea began to decrease in amplitude between 09/15/18Z and 09/16/00Z and by 09/16/12Z the ridge had flattened out as it shifted towards the east. Due to the weakening of this ridge, the upper-level low was able to accelerate eastward across Italy between 09/16/00Z and 09/16/12Z, while the surface cyclone remained nearly stationary just to the east of Corsica during that time. This eastward acceleration of the upper-level low appears to have led to the decoupling of the upper-level cyclone from the lower-level cyclone shortly after crossing into the Tyrrhenian Sea. As a result, northwesterly flow located along the western side of the upper-level low became vertically aligned over the Tyrrhenian Sea and the surface cyclone. This northwesterly flow continued over the Tyrrhenian Sea through 09/17/00Z. Since the CTRL1 surface cyclone began to move towards the southeast around 09/16/12Z which coincided with the time that the northwesterly flow moved over the Tyrrhenian Sea, it appears as though this northwesterly upper-level flow may have aided the propagation of the surface cyclone towards the southeast along the western side of Italy.

6. CONCLUDING REMARKS

Two mesoscale cyclones observed during the MAP, which exhibited dramatically different track characteristics as they approached the Apennines, were studied. The IOP-8 Genoa cyclone slowed down along the west side of the mountain and accelerated over the Apennines, but appeared to be slightly deflected towards the south and became discontinuous as it crossed the Apennines. For IOP-1, the Genoa cyclone appeared to be deflected towards the southeast as it approached the upstream side of the Apennines, but remained on the western side of the mountain range until reaching the southern end of Italy.

We examined to what extent the control parameters, V_{max}/Nh and *U/Nh,* proposed by Lin et al. (2005) can dictate the degree of track deflection of the MAP IOP-1 and IOP-8 Genoa cyclones as they approach the Apennines. The control simulations for IOP-1 and IOP-8 produced cyclones that had similar V_{max}/Nh as each other, and yet their tracks were significantly different. Therefore, the value of V_{max}/Nh did not provide any indication as to the track type in this case. Since the basic flow was different between each control simulation, a sensitivity experiment was performed in which the Apennines were removed in each case to determine if a large value of *U/Nh* is indicative of less deflection for the IOP-1 and IOP-8 Genoa cyclone tracks. The IOP-8 cyclone easily crossed Italy with a generally straight track, while the IOP-1 cyclone continued to move towards the southeast. This showed that orographic blocking by the Apennines did not play significant role in the southeastward track of the IOP-1 cyclone and, thus, it appears that the IOP-1 cyclone track is not really a case of track deflection, but rather a case of cyclone movement.

Since the Apennines did not influence the southeastward movement of the IOP-1 cyclone, other factors (interaction with the mountains of Corsica, frictional effects, and synoptic forcing) were examined to determine the role they played in the southeastward cyclone movement. In the simulations in which the mountains of Corsica were removed and the effects of friction were suppressed, respectively, the IOP-1 surface cyclone still continued to follow a track towards the southeast. The synoptic flow was then examined to determine its role in dictating cyclone movement. For the IOP-8 case, the downstream side of the upper-level trough generally aligned vertically with the dominant surface cyclone throughout the simulation. However, with IOP-1, the upper-level closed low appeared to decouple from the surface cyclone over the Tyrrhenian Sea when the upper-level ridge weakened over the Adriatic Sea. This allowed the upper-level low to accelerate towards Italy while the surface cyclone still remained in the Tyrrhenian Sea. The surface cyclone was then under northwesterly flow aloft, which appeared to aid the propagation of the surface cyclone towards the southeast along the western coast of Italy.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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