Chapter 3. Synoptic and Mesoscale Environments Conducive to Heavy Rainfall Associated with an Orographic Rain Event: Numerical Simulations of MAP IOP-2B.

3.1 Introduction

The European Alps is a region that experiences heavy rainfall events, especially in autumn (Frei and Schär, 1998) with climatological precipitation maximums occurring in the Ticino-Lago Maggiore and Veneto-Friuli regions (Fig. 3.1). There have been several recent events in these areas and other Alpine regions (Buzzi et al., 1998; Massacand et al., 1998; Sénési et al., 1996, Buzzi and Foschini, 2000; Tripoli et al., 2000). These events exhibit some common synoptic and mesoscale environments conducive to heavy rainfall in the Alps. These include the presence of a prefrontal low-level jet (LLJ) transporting moisture into the Alps, an upper-level trough and associated potential vorticity (PV) anomaly or streamer, and the northward transport of hot, dry African air (Tripoli et al, 2000).

The prefrontal southerly jet has been found in several cases: (a) Vaison-La-Romaine (1992) (Sénési et al., 1996; Massacand et al., 1998; Buzzi and Foschini, 2000), (b) Genoa (1992) (Tripoli et al., 2000), (c) Brig (1993) (Massacand et al., 1998; Buzzi and Foschini, 2000), (d) Piedmont (1994) (Buzzi et al, 1998; Massacand et al., 1998; Buzzi and Foschini, 2000), (e) South Ticino (1995) (Massacand et al., 1998; Buzzi and Foschini, 2000), (f) Friuli (1995) (Buzzi and Foschini, 2000), (g) Friuli (1998) (Tripoli et al., 2000) and an ensemble of five October events (Fehlmann and Quadri, 2000). As previously noted, the LLJ is found
ahead of an approaching cold front associated with a surface cyclone usually off the western European coast. The role of the LLJ is to transport moist Mediterranean air into the southern Alps. As the flow impinges on the terrain, it is forced upward, leading to condensation and precipitation. The warming of the atmosphere from the latent heat released by condensation can lead to changes in the orographic flow field and precipitation distribution and amounts (Buzzi and Foschini, 1998).

Another factor found in several cases is the presence of an upper-level trough and PV. These cases include the above cases with the exception of the Genoa and Friuli (1998) cases. Massacand et al. (1998) hypothesized that the advection of upper-level PV anomalies (or streamers) toward the Alps is central to rainfall on the southern slopes of the mountains. The advection of the PV streamer south of the Alps can lead to several things: i) an enhancement of the southerly LLJ, ii) reduction of the static stability under the streamer, and iii) ascent on the PV streamer's forward flank to trigger or enhance convection (Massacand et al., 1998). These PV streamers are often oriented north south, reaching from northern Europe into the Alps.

Another feature associated with the upper-level trough is the presence of an upper-level jet streak. The jet streak can affect regions of upward motion and precipitation by the transverse circulations around the jet entrance and exit regions with rising motion at the surface in the right entrance region and left exit regions of the jet streak.

It has also been found that the advection of hot, dry African desert air towards the Alps can affect precipitation in the Alpine region. Tripoli et al. (2000) simulated the Genoa (1992) and Friuli (1998) events and found that warm desert air was drawn off the Saharan boundary layer. This air was then transported northward over the cooler marine boundary
layer over the Mediterranean Sea forming a capping inversion and elevated mixed layer (EML). They also found the EML interacted with the moist LLJ to allow the moist entropy under the EML to build. This would create a scenario similar to the "loaded gun sounding" - a moist shallow marine layer capped by a strong inversion with warm dry air aloft (Miller, 1972). For the Genoa case, the EML and associated stability led to the formation of an upward surface "barrier convergence" zone south of the Alps. This zone funneled the surface flow eastward to Genoa and led to deepening of the moist layer along the coast. This convergence was not found for the Friuli case.

Tripoli et al. (2000) performed sensitivity tests to determine the role of various mountain ranges, the Alps, Sardinia and Corsica, and the Atlas Mountains in North Africa. The tests revealed that the Atlas Mountains initially funneled the broad flow off the Sahara into a narrow stream toward Genoa and the orography of Sardinia and Corsica helped maintain the focus. Tests for the Friuli case revealed the Adriatic basin channeled flow toward Friuli.

In summary, from a review of previous Alpine rain events, several key factors come into play over the Alps. A prefrontal southerly low-level jet brings in moist air that impinges against the mountains and is forced to rise by the orography. This LLJ is coincident with a southward propagating PV streamer, which can further enhance ascent. The presence of an upper-level jet streak can also enhance ascent in the region. The hot dry African air being transported aloft can affect stability and convection and enhances moist entropy in the layer containing the LLJ. A summary of key ingredients for orographic precipitation can also be found in Lin et al. (2001).
3.2. Mesoscale Alpine Programme (MAP)

Because of the events of the previously mentioned studies, the Mesoscale Alpine Programme (MAP) was developed to better understand the mechanisms that lead to heavy orographic rainfall. Some of these mechanisms include orographic effects, PV anomalies and banners, gravity waves, and mountain airflow. For more information about MAP, see Bougeault et al. (2001).

The research proposed for this study will focus on one case from MAP, IOP-2B from September 1999. Observations from the MAP SOP (Special Observing Period) and NCAR/PSU MM5 (V3) model simulations will be used in this study.

3.3. Observation analyses

In order to provide an understanding of the events surrounding IOP-2B, analyses of observations were performed. Following are surface analyses, upper air analyses, radar, and satellite analyses.

3.3.1 Surface analyses

Subjective analyses of surface observations are shown in Fig. 3.2. At 0000 UTC 19 September, a cyclone was located near the British Isles. An anticyclone was over eastern Europe and Russia. Over northern Italy, there was a ridging in the isobars as the southeasterly flow from the Adriatic Sea was blocked to the west by the Alps. In reaction to this ridging, the trough extended east into Switzerland and Austria.

Twenty-four hours later, on 0000 UTC 20 September, the cyclone remained over the eastern Atlantic and based on the observations, propagated eastward into France. The
ridging over the Alps persisted as the flow continued to be blocked by the mountains (note cross isobar flow in northwest Italy). West of Spain, a secondary trough had formed south of the main storm, helping to create unsettled conditions over the Mediterranean. Six hours later, at 0600 UTC, the main cyclone was still centered over England. The trough axis of the secondary trough in the Mediterranean propagated eastward to just west of Sardinia and Corsica. By now, the flow in Italy was from the southwest as indicated by the 20 m s\(^{-1}\) observation along the coast with east and northeast winds around the slopes of the Alps and Apennines. These three flow directions created a confluence and possible convergence zone over the Alps near the LMTA. This converging flow has been noted in previous Alpine cases, such as the 1994 Piedmont flood (Buzzi et al., 1998). The flow pattern persisted through 1200 UTC (Fig 3.2d).

3.3.2 Upper air analyses

At the 850 hPa level at 0000 UTC 19, the trough associated with the surface cyclone was located over southern England and western France (Fig 3.3a). A general southwest flow pattern was present over the Mediterranean. Winds over Italy were generally from the south and southeast toward the low pressure. At 300 hPa, the trough was anchored over the eastern Atlantic with a ridge located over eastern Europe. A southwest flow was present over the Alps with diffuence evident in the wind observations (Fig. 3.3b).

Twenty-four hours later, the low-level trough had propagated east (Fig. 3.4a). A low-level jet (LLJ) with 20 m s\(^{-1}\) winds was observed near the French-Italian border. Winds near the LMTA were from the southwest and southeast. At upper levels, the ridge was amplifying east of Italy as the trough propagated eastward. Diffuence was present over Italy as
indicated by the wind observations and height contours. An upper-level jet was located over southern Spain and stretched northeast toward Italy (note gradient of height contours and 45 m s\(^{-1}\) observation in Spain).

By 1200 UTC 20, the core of the low-level trough was apparent over Ireland and England as the trough continued to propagate east (Fig. 3.5). By now, the general wind direction in Italy was from the southwest. At the 300 hPa level, the jet had propagated around the base of the trough and was now located near Italy. The outer fringes of the jet were located in northwest Italy as evidenced by the wind observations. Also, diffluence was present as southerly winds were in western Italy and southwesterly winds were east of those observations. This upper-level diffluence, coupled with low-level confluence could aid in the upward motion and rainfall formation over the LMTA.

In order to provide verification for the model simulations, two stations were selected for observed soundings. These stations were Milan, Italy (MIL) and Cagliari, Sardinia (CAG). Milan was representative of the environment of the LMTA while Cagliari was representative of upstream conditions and influences from Africa.

The soundings are shown in Fig. 3.6. Soundings at CAG were taken at 1200 UTC 19 and 0000 UTC 20 September. MIL soundings were plotted for 0000 UTC and 1200 UTC 20 September. The Cagliari sounding for 1200 UTC 19 exhibited a shallow layer and an almost moist adiabatic lapse rate under a shallow inversion with a lifting condensation level (LCL) of 872 hPa. Above this inversion was a very deep dry layer of possible African origin extending from about 950 to 350 hPa. The lapse rate in this layer was between the dry and moist adiabatic lapse rates, showing slight conditional instability and represented the elevated mixed layer. Winds below 900 hPa were southerly and veered to the southwest and west-
southwest with height, indicating possible quasi-geostrophic warm thermal advection as the low-level trough transported warm air over the North African and southern Mediterranean regions northward. The CAPE value for this sounding was 0 J kg\(^{-1}\).

By 0000 UTC 20, the wind profile was similar as 12 hours earlier, low-level southerly winds veering to southwest. The low levels, below 925 hPa were somewhat moist with the inversion near the surface increasing in strength from 1200 UTC 19. The dry layer above the inversion had become moister since 1200 UTC 19. For this sounding, the LCL was 965 hPa with 0 J kg\(^{-1}\) of CAPE. Both the 1200 UTC 19 and 0000 UTC 20 soundings appear similar to the Miller Type I (the loaded gun) sounding (Miller, 1972) with a moist low-level, inversion, and dry layer. This is consistent with the findings of Tripoli et al. (2000) for the Genoa and Friuli cases.

The MIL sounding for 0000 UTC 20 exhibits different behavior from the CAG sounding for the same time. Unlike CAG, where there is a dry layer at the mid-levels of the atmosphere, the MIL sounding exhibited a fairly moist atmosphere. The LCL of the sounding was 945 hPa and 195 J kg\(^{-1}\) of CAPE were calculated. Winds at the surface were from the southeast, and veered to the southwest with height. The sounding appeared to be a Type II sounding (Miller, 1972) in that the atmosphere was fairly moist and the sounding was conditionally unstable.

Twelve hours later, the LCL had risen to 895 hPa and the CAPE was 82 J kg\(^{-1}\). The low-level winds were still southeasterly and veered to southwest then appeared to back to southerly above 400 hPa. The atmosphere was very moist and still appeared to be conditionally unstable.
3.3.3 Radar and rain gauge analyses

Radar imagery for 0000 UTC 19 showed little rainfall activity in Italy with only a few showers in southern France (Fig 3.7a). By 0000 UTC 20, a large area of rainfall had developed over western France and extended into Italy. Rainfall rates near the LMTA were between 3 and 10 mm per hour. Six hours later, the rain shield in France had decreased in coverage while the rainfall in western Italy increased near the confluence zone analyzed in the surface observations. Rainfall rates remained between 3 and 10 mm per hour. By 1200 UTC, rainfall was beginning to move out of the LMTA with rain just ending south of the LMTA. Rainfall rates still remained at the same level and given this steady rainfall rate since 0000 UTC 20, rainfall totals would be approximately 120 mm in the 12 hour period over the LMTA.

The 48-hour accumulated rainfall from the rain gauge network in the Alps is shown in Fig. 3.8. The period of accumulation was from 0000 UTC 19 to 0000 UTC 21 September. The highest accumulation was over 275 mm southwest of Lago Maggiore. In this region, the gradient of rainfall totals was large showing the local effects of the individual mountains. Several other local maxima in the rainfall could be seen, including a 125 mm maximum near the Gulf of Genoa in Italy and another along the French Italian border. Maxima along the Alps (175 and 225 mm) were also observed.

3.3.4 Satellite analyses

Meteosat infrared and water vapor imagery can supplement the surface and upper air analyses given the limited domain of the observations. At 0130 UTC 19, the circulation of the surface cyclone can be seen in the infrared (IR) imagery (Fig. 3.9a). The satellite
imagery gives a more accurate placement of the cyclone west of Ireland, farther west than the observations. The clouds associated with the storm stretch from England down to the Strait of Gibraltar.

By 0130 UTC 20 (Fig. 3.9b), cold cloud tops indicative of convection were over western Italy and eastern France, corresponding to the rainfall seen in the radar imagery. At 0600 UTC, northern Italy was entirely under the cold tops as the clouds continued to propagate eastward with the cyclone (Fig. 3.9c). By 1200 UTC 20 (Fig. 3.9d), the trough had already moved to the east of the LMTA. When the IR images are animated, the southerly transport of moist air from the Mediterranean to the LMTA can be clearly seen.

The upper-level trough and jet structure can be clearly seen in the water vapor imagery (Fig. 3.10) starting at 0200 UTC 19. The gray area is located to the west of the upper-level jet and can be used to track its propagation, which is consistent with the upper-level sounding observations. By 1200 UTC 20, the jet was located near the LMTA region of the Alps. This jet possibly provided energy to aid in the development of rainfall in the region.

3.3.5 Summary of observations

In summary, several possible key features in the development of rainfall over the LMTA were observed. One, a surface cyclone to the northwest provided a southerly and southwesterly flow into the LMTA. This flow over the Mediterranean was moist and when impinging upon the Alps and Apennines, ascended and led to rainfall development. Analyses of radiosonde observations at 850 hPa showed that the southerly flow persisted vertically and a low-level jet developed, acting as a focus of the moisture transport. Like the
surface flow, this LLJ impinged upon the mountains, leading to ascent and rainfall development.

At upper levels, 300 hPa, a strong trough propagated across the LMTA from the west. To the east of the LMTA, a ridge existed and this ridge appeared to remain fairly stationary. As the ridge remained stationary and the trough moved eastward, the ridge became amplified and a diffluent flow pattern developed over the LMTA. The diffluence, coupled with low-level confluence, could further aid in the development of the rainfall. Also, a jet propagated around the base of the trough and at the time of heavy rainfall (0000 UTC - 1200 UTC 20), the jet was just west of the LMTA. Ageostrophic circulations associated with the jet also could further aid in rainfall development.

Also a key ingredient in the rainfall development was the mountain range itself. The geometry of the Alps and Apennines created a confluent flow pattern at the surface as southeasterly winds from the Adriatic were blocked to the east and became juxtaposed with southwesterly and southerly winds from the Mediterranean.

From the observations, a hypothesis is that moist low-level flow (surface and lower levels of the atmosphere) from the south impinged upon the southern Alps and Apennines. This flow became juxtaposed with an easterly flow caused by mountain blocking in eastern Italy, creating a confluence and convergence zone. The confluence alone could create ascending motion but the impinging flow upon the mountains could also create rising motion. At lower levels, the southerly flow was in the form of an LLJ, acting as a focus for moisture flow. Upper-level diffluence and a jet aided in the development of upward motion. The mountains acted to keep the precipitation focused in one area.
3.4. Model and simulations

To test the hypothesis for rainfall development of IOP-2B, the PSU/NCAR MM5 (Version 3) model will be used. Three simulations will be performed: 1) a full terrain simulation, denoted FULL, in which the model terrain is an accurate representation of the physical terrain of Europe and North Africa, 2) a terrain sensitivity simulation, denoted AFRICA0, in which the terrain of North Africa is reduced to zero and, 3) a terrain sensitivity simulation, denoted ZERO, in which the entire model domain terrain is set to zero. The purpose of AFRICA0 is to study the role that the Atlas Mountains of northern Africa play in the flow of air toward the Lago Maggiore region. The purpose of the ZERO simulation is to see the effects of the dynamics of the atmosphere independent of terrain on rainfall production over the Lago Maggiore region.

Each simulation will be integrated for 48 hours and initialized at 0000 UTC 19 September. The area being modeled is shown in Fig. 3.11 with three domains: Domain 1 (45 km, 85x91), Domain 2 (15 km, 121x121), and Domain 3 (5 km, 121x121). Also shown in the southern part of the domain, is the region where the African terrain is to be reduced. Presented results of the simulations will focus on Domains 1 and 2. For all domains, the Kain-Fritsch convective scheme (Kain and Fritsch, 1993), Blackadar PBL scheme (Blackadar, 1976, Blackadar 1978), and simple ice microphysics were used to parameterize the convection, boundary layer, and microphysics, respectively.

3.5. Model results

Domains 1 and 2 results follow for the FULL, AFRICA0, and ZERO simulations for the period 0000 UTC through 1200 UTC 20 September.
3.5.1 Sea level pressure and surface winds

The Domain 1 surface winds and sea level pressure field for all three simulations are shown in Fig. 3.12. At 0000 UTC 20 September, the surface cyclone was present west of France with a pressure of 982 hPa (Fig. 3.12a). Over the western Mediterranean Sea, there was a secondary trough just south of France with winds over the French-Italian border from the south. Winds between Corsica and Italy were from the southeast as were the winds over the Italian Alps. Two distinct converging flows could be seen: the southerly flow west of Corsica and Sardinia near the French-Italian border, denoted as F1, and the southeasterly flow east of Corsica and Sardinia, denoted as F2. The flows converged along the French Italian border near the coastline. This pattern persisted through 1200 UTC 20 September as the surface cyclone neared the northern French coast. Overall, the model flow pattern agreed well with observations.

Several differences in the surface fields were seen between the FULL and AFRICA0 simulations. At 0000 UTC, the closed low that was present over Algeria in the FULL simulation was no longer evident. Instead, a trough had formed over the region. This occurred as the westerly winds entering west Africa from the Atlantic were able to penetrate more to the south and east. Previously in the FULL simulation, the mountains in Morocco and Algeria blocked the flow. Also, over Tunisia and eastern Algeria, the mountains blocked the easterly flow to the north, allowing for the development of the low. In the AFRICA0 simulation, the lack of terrain allowed the easterly flow to propagate farther west, eliminating the low in conjunction with the incoming westerly flow.

At 0600 UTC, the trough associated with the low west of France extended down to the African coast (Fig. 3.12e as denoted by the 1004 hPa isobar). Also, winds in the southern
Mediterranean were about 5 m s$^{-1}$ stronger in the AFRICA0 simulation. This was due to the stronger pressure gradient because of the southern extension of the trough. As at 0000 UTC, the low present over Algeria in the FULL simulation was no longer present in the AFRICA0 simulation. Over western Algeria, south of Morocco, the winds had changed from westerly to northerly flow as the mountain ridge was eliminated because of the flat terrain.

By 1200 UTC, conditions over Italy and the Mediterranean appeared to be similar in both simulations. Over Morocco, the lack of terrain allowed for more southeasterly penetration of the winds in the AFRICA0 simulation.

As with the AFRICA0 simulation, the previously existing low in Algeria in the ZERO simulation was an extension of the surface trough north of Africa (Fig. 3.12g-i). Also the ridge to the east over Libya extended farther south, as the mountains were no longer present to block the flow. Over Italy, where the Alps were located, the pressure ridging seen in the other simulations was gone, as now the winds were southeasterly instead of easterly due to terrain effects. This reduced the surface convergence, which previously aided in precipitation formation.

### 3.5.2 850 hPa features

A key ingredient of the development of past Alpine rainfall events was the presence of a low-level jet (Lin et al., 2001). At 0000 UTC 20 September, a low-level region of enhanced southwest winds was located just south of the Italian coast, close to the target area as indicated by observations (Fig. 3.13a). To the southeast and east of this region, there were two other regions of enhanced flow over Sardinia and over the North African coast. Six hours later, the two local wind maxima near Italy had merged and were penetrating the
Italian coast. This region of enhanced flow then continued to propagate east ahead of the trough.

At 0000 UTC, differences in the LLJ between the FULL and AFRICA0 simulations were evident. For the AFRICA0 850 hPa height field, the gradient was much smoother (Fig. 3.13d-f) than for the FULL simulation. In the FULL simulation, a ridge was located over Morocco, reflecting the influence of the mountains. This in turn, affected the upstream height gradient and wind field. The 20 m s\(^{-1}\) isotach was much smaller in spatial coverage in the AFRICA0 simulation. This is supported by the weaker gradient between the 1,440 and 1,410 m height contours. However, the relative position of the LLJ relative to Italy was largely unchanged.

By 0600 UTC, the AFRICA0 LLJ was oriented north south, stretching from interior Italy to Tunisia (Fig. 3.13e). It was also narrower than the FULL LLJ. Winds in the AFRICA0 LLJ were from a more southerly direction. Also, the trough over Algeria that existed in the FULL simulation no longer existed in the AFRICA0 simulation.

At 1200 UTC, the winds over Italy and near Corsica and Sardinia appeared to be mostly comparable to the FULL winds. Differences could still be seen over Africa as the height gradient changed without terrain. Winds were somewhat stronger and consistently from the northwest and west while winds were variable for the FULL simulation.

In the ZERO simulation, the LLJ appeared to propagate faster into Italy because at 0000 UTC, the LLJ had penetrated to the Italian-Swiss border (Fig. 3.13g) and extended back to Algeria. By 0600 UTC, the ZERO LLJ was more oriented north to south, similar to the AFRICA0 LLJ. Also the winds entering into the LMTA were stronger than the FULL winds as evidenced by the 30 m s\(^{-1}\) isotach. The jet continued to propagate north as it was entering
Germany by 1200 UTC. The faster propagation of the LLJ was due to removal of the mountains, which partially slowed the flow due to friction.

Previous studies indicated that the role of the low-level jet (LLJ) was to transport moist warm air into the Alpine region. To see these characteristics at the 850 hPa level, the equivalent potential temperature, \( \theta_e \) was analyzed. Initially, at 0000 UTC 19 September, the higher \( \theta_e \) values were located over Africa with a maximum over 338 K (not shown). There was also a local maximum of 338 K over the Alps near LMTA.

By 0000 UTC 20 September, two streams of higher \( \theta_e \) air were progressing northward toward LMTA. The first stream was from the Mediterranean area of North Africa while the second stream was from the Atlantic coast of North Africa (Fig. 3.14a). The tongue of high \( \theta_e \) air from Africa appeared to be from a pool of high \( \theta_e \) air that extended back into central and southern Libya. Also, coincident with the location of the enhanced southwesterly flow (see Fig 3.13) was an area of locally high \( \theta_e \) air off the eastern coast of Spain. Six hours later, the predominant flow of high \( \theta_e \) air was from North Africa, with high values also along the Italian coast as the 850 hPa jet impinged the coast. By 1200 UTC 20 September, the two-pronged stream had reappeared with high \( \theta_e \) air flowing from North Africa and the Atlantic coast of Africa.

Given that differences existed in the 850 hPa wind field, the advection of the 850 \( \theta_e \) field would also change between simulations. The AFRICA0 \( \theta_e \) field is also shown in Fig. 3.14. At 0000 UTC, the 328 K \( \theta_e \) tongue was slightly farther north over Sardinia as slightly stronger winds just north of the African coast advected the high \( \theta_e \) air. By 0600 UTC, the AFRICA0 328 K tongue was located in southern Italy while the FULL 328 K tongue was still south of the coast. Also, the FULL tongue was farther east than the AFRICA0 tongue.
This was due to a more southwesterly fetch in the winds in the FULL simulation. The AFRICA0 winds were more southerly, advecting the air farther north instead of east. By the end of the heavy rainfall period, at 1200 UTC, the AFRICA0 328 K tongue was similar in position as the FULL tongue, although slightly wider.

At 0000 UTC, in the ZERO simulation, the 328 K tongue from Africa extended farther north than the FULL 328 K tongue. At this time, the tongue extended to Corsica in the ZERO simulation while the tongue extended to Sardinia in the FULL simulation. However, the local $\theta_e$ maximum north of the Balearic Islands (east of Spain) in the FULL simulation was much smaller in coverage in the ZERO simulation. Further differences were seen over northwest Africa as the wind flowed around the base of the trough. As with the FULL simulation, the pool of high $\theta_e$ air extended into Libya.

By 0600 UTC, the faster wind speeds in the ZERO simulation advected the 328 K tongue to the Italian-Swiss border while in the FULL simulation the tongue was just reaching the western Italian coast. At 1200 UTC, the 328 K tongue was approaching the Swiss-German border with a 336 K maximum in Italy, east of the LMTA, extending along the western coast of the peninsula. This 336 K maximum was not seen in the FULL simulation.

It has been found from observations and the simulations that there existed a LLJ that transported high $\theta_e$ air into the LMTA. This is consistent with the ingredients of Lin et al. (2001). This transport of high $\theta_e$ air allowed for the possibility of convection as it enhanced the potential instability. In order for rainfall to develop, there must be a source of moist air to reduce the potential instability.

At 0000 UTC, the FULL simulated relative humidity showed very moist air (RH > 70%) over the LMTA (Fig. 3.15a) with moist air extending southwest and west around the base of
the trough. High humidities persisted for the next 12 hours over the LMTA with the axis of the LLJ becoming aligned with the axis of the high RH.

As with the FULL simulation, the AFRICA0 simulation showed high RH values over the LMTA at 0000 UTC (Fig. 3.15d). The stream of moisture over the western Mediterranean was narrower than the FULL stream. The RH did appear to be similarly distributed in both simulations. Overall, the AFRICA0 simulation was similar in RH distribution to the FULL simulation at the large scale. No major differences were evident.

The ZERO simulated RH did exhibit some differences over the LMTA relative to the other two simulations (Fig. 3.15g-i). In the previous simulations, the entire Italian Alpine region was over 70%. In the ZERO simulation, high RH values did not extend as far east of the 10°E meridian as in the other simulations. Also, over Spain and northwest Africa, the area of high RH had decreased with the stream of moisture between northern Africa and Italy being very narrow. The smaller areas of high RH persisted through 1200 UTC as the moisture flowed around the trough. A possible reason for the decrease in coverage of high RH values over Italy was the lack of blocking by the mountains, which could trap the moisture within the mountain region and increase the low-level convergence of air.

3.5.3 300 hPa heights and winds

For all three simulations, the upper-level features were very similar and there were few readily evident differences. Therefore the FULL Domain 1 300 hPa features will be discussed and assumed to be relevant for all three simulations.

The initial Domain 1 300 hPa heights and winds are shown in Fig. 3.16a. At this time, the large upper-level low was located west of Ireland, coincident with the location of the
surface storm. A broad jet wrapped around the base of the trough with the stronger winds over Portugal and Spain (40-45 m s$^{-1}$) and with the core of the jet (winds over 50 m s$^{-1}$) located over the eastern Atlantic just west of Portugal. A second jet was located over Africa. Over the Italian Alps, winds were from the west-southwest with some diffluence already present (as indicated by the height lines), agreeing well with observations. Twenty-four hours later, a smaller jet, embedded within the main jet associated with the trough, was located over eastern France (Fig. 3.16b). This jet had its beginnings along the French-Spanish border at 1200 UTC 19 September (not shown). Note that winds within this jet were over 40 m s$^{-1}$ and slightly ageostrophic toward the lower heights. Also, over the LMTA, diffluence was present, aiding in the ascent of air parcels at lower levels.

By 0600 UTC, the jet entrance region was west of the LMTA with winds near 50 m s$^{-1}$ in the entrance region (Fig. 3.16c). Also a second wind maximum was located just south of the French Mediterranean coast with winds over 40 m s$^{-1}$. By 1200 UTC, the two jets appeared to have merged with the entrance region just west of the LMTA.

### 3.5.4 Surface and upper-level divergence

This section will discuss the modeled surface and upper-level (300 hPa) divergence patterns for all three simulations. For the surface, areas of interest are those of negative divergence, or convergence. At the 300 hPa level, areas of positive divergence are of interest. The reasoning for choosing convergence (divergence) at the surface (300 hPa) is that areas that have upper-level divergence juxtaposed over areas of low-level convergence are conducive to upward vertical motion, particularly in the presence of warm air advection and orographic uplift.
The FULL, AFRICA0, and ZERO simulated surface and 300 hPa divergence fields are shown in Figs. 3.17, 3.18, and 3.19 respectively for 0000, 0600, and 1200 UTC September. Also shown is the 700 hPa vertical velocity (upward motion shaded over 5 cm s\(^{-1}\)) field to give an idea of the vertical motion at lower mid levels of the atmosphere. At the surface in the FULL simulation, convergence was present along the western slopes of the Alps, near the LMTA. There was also a zone of convergence extending from the western coast of Italy southwestward across the Mediterranean. The surface convergence was juxtaposed by weak upper-level divergence (Fig. 3.17a). The 700 hPa vertical velocities do show upward motion was occurring over the surface convergence regions. Along with the weaker upper-level divergence, this seems to indicate that the low-level convergence was the main reason for the upward vertical motion.

By 0600 UTC, the main concentrated area of convergence was along the Alps and Apennines with some localized regions over the Mediterranean. The convergence in the Alpine region was due to the southerly winds off of the Mediterranean Sea becoming juxtaposed with easterly and southeasterly winds from the Po Valley. At this time, there appeared to be more upper-level support as stronger divergence was juxtaposed over the low-level convergence. However the low-level convergence was still stronger in magnitude (\(-65 \times 10^{-5} \text{ s}^{-1}\) at the surface, \(15 \times 10^{-5} \text{ s}^{-1}\) at 300 hPa). Note there was at least some weak vertical motion along the Alpine slopes.

Six hours later, three local minima in the divergence field (maximum convergence) were located along the slopes of the Alps with other minima along the western Italian coast. Surface convergence was still stronger in magnitude relative to the 300 hPa divergence (\(-95 \times 10^{-5} \text{ s}^{-1}\) at the surface, \(15 \times 10^{-5} \text{ s}^{-1}\) at 300 hPa).
and $10 \times 10^{-5} \text{ s}^{-1}$). Upper-level divergence was mostly concentrated south of the LMTA. A broad area of upward vertical motion at 700 hPa was also present.

The AFRICA0 surface convergence at 0000 UTC was similar in distribution to the FULL simulation over the Alps, but differences were evident over the Mediterranean (Fig 3.18a). While the FULL simulated convergence was continuous from the Italian coast southward to the 40°N parallel, the AFRICA0 convergence was divided into two regions with one over the Italian coast and the other just northwest of Sardinia. South of Sardinia, the convergence was weaker by $5 \times 10^{-5} \text{ s}^{-1}$ and concentrated in a narrow zone in the AFRICA0 simulation. The upper-level divergence was also different between the simulations. West of Spain, the AFRICA0 simulated 300 hPa divergence was weaker and smaller in coverage than the FULL simulation. Also, the area of divergence west of Sardinia present in the FULL simulation was shifted southeast and was weaker in the AFRICA0 simulation. Additionally, the distribution of 700 hPa upward motion changed with the upward motion in the Alps being more concentrated in coverage than in the FULL simulation. These differences between the divergence fields (surface and upper-level) and 700 hPa vertical velocities were most likely due to differences in diabatic heating as inferred from rainfall patterns and convection. Rainfall distribution will be discussed in more detail in the next section.

Differences persisted through 0600 UTC where most differences at the surface were over the Mediterranean where wind flow from Africa was most likely to impact the physics (Fig. 3.18c). At upper levels, the divergence differed in that the AFRICA0 simulated 300 hPa divergence covered a broader area over western Italy and the Apennines than the FULL simulated divergence.
At 1200 UTC, the AFRICA0 simulation, while exhibiting a similar pattern to the FULL simulation in that there were three maxima over the Alps, did not simulate as strong convergence at the surface (Fig. 3.18b). The maxima were not as evident as in the FULL simulation (Fig. 3.17). The maxima over the western Italian coast were also weaker than the FULL, by about $10^{-4}$ s$^{-1}$. Convergence over Sardinia was also weaker. At 300 hPa, the divergence over the Alps for the AFRICA0 simulation appeared to have a northwest to southeast orientation while the FULL divergence was oriented east to west. While both simulations exhibited 700 hPa rising motion, the AFRICA0 simulation showed rising motion over the western Alps and Apennines while the FULL simulation simulated more rising motion just west of the LMTA. Also, the AFRICA0 simulated rising motion was less continuous from Italy south toward Sardinia.

Without the mountains over Italy, the ZERO simulated surface convergence was much weaker than the FULL or AFRICA0 simulated convergence (Fig. 3.19). There were only seven areas of weaker convergence with none over the former Alps. Without the Alps, flow was mostly southerly (see Fig 3.12). At the 300 hPa level, divergence was also weaker, with only a few areas of divergence. Note that even without the mountains, there was rising motion at 700 hPa, near the former Alps. Rising motion was also evident over the Mediterranean where the surface convergence and upper-level divergence were juxtaposed. Note the complete absence of rising motion in the former concave region of the Alps.

Throughout the rest of the period, up to 1200 UTC, the ZERO convergence was much weaker and only located in a few places. The convergence in the ZERO simulation was most likely due more to the y-component ($\partial v/\partial y$) being negative as faster southerly winds became juxtaposed with slower southerly winds near Italy instead of a more confluent flow pattern as
seen in the other simulations with mountains. The upper-level divergence for the ZERO simulation depicted stronger divergence over northern Italy than in the FULL but by 1200 UTC, there was very weak divergence in the ZERO simulation. Also note that at 1200 UTC, the ZERO 700 hPa rising motion was distributed in a narrower zone than in the FULL simulation and was oriented more like a frontal zone.

From these three simulations, it can be shown that the Alps did play an important role in the development of surface convergence, important for rainfall formation. The African terrain played a role in upstream convergence, ultimately affecting the development of convergence over the Alps. Upper-level divergence was also affected by the mountains and upstream conditions, most likely due to the effects of different convection patterns and latent heat release on the upper-level height and wind fields. However, upper-level divergence was present in all three simulations, with and without mountains.

### 3.5.5 Model soundings

To aid in model verification, model soundings were calculated for CAG and MIL and compared to the previously discussed observed soundings. The FULL, AFRICA0, and ZERO soundings for CAG for 1200 UTC 19 and 0000 UTC 20 are shown in Fig. 3.20. Also shown on the soundings are parcel information (i.e. CAPE, LCL, LFC, etc.) and the parcel temperature when lifted from the surface (as indicated by the dashed line). Overall, for 1200 UTC 19, the three soundings appear very similar in appearance. All three show a low-level layer with nearly adiabatic lapse rates overlaid by a very weak inversion. Above this inversion was a dry layer, although not nearly as dry as the observed sounding. All three soundings also show that above 700 hPa, there was the potential for parcels to rise. The LCL
levels included: 844, 860, and 876 hPa for the FULL, AFRICA0, and ZERO soundings. These gave differences of 28, 12, and 4 hPa between the model soundings and the observed soundings. The FULL and AFRICA0 soundings showed low CAPE values of 10 and 58 J kg\(^{-1}\) respectively with the ZERO sounding having no CAPE. Below 500 hPa, the model soundings were conditionally unstable and above 500 hPa were weakly stable and conditionally unstable. The wind profiles agree well with the observed sounding in terms of speed and shear. Winds veer from south-southwest to southwest and west-southwest with height.

The 0000 UTC 20 model soundings differed from the observed sounding in that all three soundings had large values of CAPE (859, 775, and 471 J kg\(^{-1}\) for the FULL, AFRICA0, and ZERO soundings respectively) while the observed sounding had no CAPE. The overall profile of the observed sounding was matched by the model soundings, however more detail appeared in the observed sounding as evidenced by the smoother profiles of the simulated soundings. The AFRICA0 and ZERO soundings differed from the FULL sounding in that the top of the low-level dry layer between 950 and 650 hPa was capped by a near equal dew-point and air temperature while the FULL sounding "cap" had a dew-point of 0°C and temperature of about 3°C. All three simulated soundings at this point were warmer than the observed sounding. The LCL of the three simulated soundings were also higher than the observed sounding. The simulated soundings looked similar to the "loaded gun soundings" although not as striking as the observed soundings.

The MIL model soundings, shown in Fig. 3.21, were similar in appearance to the observed MIL sounding for 0000 UTC 20. The model soundings differed in the drier layer between 950 and 700 hPa. All three soundings were weakly stable to conditionally unstable.
The AFRICA0 had more variability in the dew-point profile (note 0°C at 750 hPa for the AFRICA0 and greater than 0°C dew-points for the FULL and ZERO soundings). The ZERO sounding had the highest CAPE, 124 J kg⁻¹ while the LCL pressures differed by only 3 hPa and were about 15 hPa from the observed LCL. Also, from the parcel temperature profile, only the ZERO sounding exhibited the potential for parcel ascent.

At 1200 UTC 20, the three simulated soundings also showed differences in the general profiles. The AFRICA0 and ZERO soundings had more pronounced dry layers between 700 and 500 hPa than the FULL sounding, which was very moist. The dew-point and temperature differences appeared nearly constant throughout the sounding in the FULL simulation. The AFRICA0 sounding was the closest to the observed sounding in terms of the LCL (904 hPa) and only the ZERO sounding had any CAPE (207 J kg⁻¹). All three simulated soundings were weakly stable or conditionally unstable. For both times, given the potential for rising motion as indicated by the low-level convergence/upper-level divergence patterns, there was probably sufficient rising motion to lift the already moist parcels.

### 3.5.6 Rainfall

In this section, the Domain 2 6-hour accumulated and 48-hour accumulated rainfall will be discussed for each of the three simulations.

At 0000 UTC 20, rainfall was light over Italy and the Mediterranean in the FULL simulation (Fig. 3.22). The highest six-hour accumulation was 40 mm near the LMTA. In the areas surrounding the LMTA, surface convergence (see Fig. 3.17) was present as split southerly flow off the Mediterranean Sea became juxtaposed with easterly flow from the eastern part of the Adriatic. This easterly flow was originally a southeasterly flow from the
Adriatic Sea that turned to the west as the flow impinged upon the eastern Alps and was seen in the Piedmont case (Buzzi et al., 1998). The southerly flow split as it impinged upon the western Alps near the coast. Part of the flow split to the west while the remaining part of the flow remained southerly or became southeasterly.

By 0600 UTC 20 (Fig 3.22b), rainfall was more widespread with six-hour totals over 60 mm along the Alpine slopes. The rainfall extended from the slopes south past the tip of the Ligurian Apennines. The convergence and split flow that was present at 0000 UTC persisted through 0600 UTC. In the simulation, the heaviest rainfall occurred between 0600 and 1200 (Fig. 3.22b-c) UTC and was collocated with the low-level convergence and upper-level divergence. Rain had been falling along the Alpine and Apennine slopes along the coast. Three maxima were evident. Two of them were located along the slopes of the Alps in the concave region near the LMTA with the third along the coast in a pass along the Apennines.

For the AFRICA0 simulation, the 0000 UTC 20 rainfall (Fig. 3.22d) was similar to the FULL simulation for the same time. There were more isolated areas of rainfall west of Spain near the Balearic Islands and rainfall was focused in a narrow zone over the Mediterranean Sea with slightly higher totals in the AFRICA0 simulation. These areas were coincident with the surface convergence. Over the Alps, the rainfall was slightly less for the AFRICA0 simulation (note no 40 mm contour). The overall wind structure near the Alps was the same as in the FULL simulation with surface convergence and the split flow present. However, there were differences over the Mediterranean Sea. Two areas of interest in the surface wind field were detected. The first, just north of Algeria between 5°E and 10°E, was a divergence zone for the FULL simulation. Here, winds flowing around the base of the trough diverged from the winds on the northern side of the low in Algeria. With the absence
of the low in the AFRICA0 simulation, this zone became a confluence zone. Winds in this area were also stronger.

The second area of interest was along the southern edge of the rainfall stretching from the southern tip of the Alps southwestward into the Mediterranean. The winds just east of 5°E and north of 40°N were slightly stronger in the FULL simulation than the winds of the AFRICA0 simulation. However, rainfall amounts in the AFRICA0 simulation were slightly higher. One possible explanation was that the surface mixing ratios were higher south of the rainband for the AFRICA0 simulation (not shown). Even though winds were slightly weaker, the higher moisture content compensated for the weaker winds.

By 0600 UTC 20, the rainfall patterns of the two simulations became slightly different. Rainfall in the FULL simulation (Fig. 3.22b) stretched down toward Africa while the rainfall in the AFRICA0 simulation was mostly north of 40°N (Fig. 3.22e). Amounts for the AFRICA0 simulation were still slightly higher, with the rainfall distribution over the Alps relatively similar. In terms of the surface wind differences, near the southern portion of the rainfall, winds in the AFRICA0 simulation were mostly southerly while the FULL winds had a southwest component.

By 1200 UTC, rainfall totals over the LMTA were higher for the AFRICA0 simulation. There was a strong southerly flow east of Sardinia that turned to the northwest along the western coast of the Italian peninsula. This flow was stronger than the FULL flow, which led to more convection and higher rainfall amounts along the Italian coast and Apennine Mountains.

The ZERO simulated rainfall was much different than the other two simulations (Fig 3.22g-i). No confluence was present over northern Italy as there was no terrain to block and
turn the winds from the Adriatic. There was an area of rainfall near the French-Spanish border and winds were generally from the south. By 0600 UTC 20, there was still little rainfall and the only rainfall appeared near a weak confluence zone. This convergence or confluence zone formed as southerly and southeasterly flow south Italy became juxtaposed with the southwest flow associated with the cyclone over France.

By 1200 UTC, rainfall was present over the LMTA, but only 40-60 mm (Fig. 3.22i). One item of interest was that all rainfall in the ZERO simulation was oriented in a north to south orientation while rainfall in the other simulations had a west to east orientation along the Alpine slopes. This provides evidence that the mountains were a major contributor to the heavy rainfall that developed over the LMTA in that the mountains focused the airstreams and created low-level convergence.

The simulated 48-hour accumulated precipitation for the period between 0000 UTC 19 and 0000 UTC 21 September is shown in Fig. 3.23. For the FULL simulation, the highest accumulations were near the LMTA with totals over 275 mm. The gradient of rainfall from 275 to 25 mm was very large in this region. Other local maxima could be seen along the slopes of the Alps and Ligurian Apennines.

The simulated 48-hour rainfall for the AFRICA0 simulation exhibited higher totals in the western part of the Alps (Fig. 3.23b). The maximum accumulation was 300 mm near the LMTA. As with the FULL rainfall, several maxima could be seen around the region. A difference plot between the AFRICA0 and FULL rainfall quantify the surplus of rainfall in the western Alps with a maximum surplus of 120 mm (Fig. 3.24a). In eastern northern Italy, there was a negative difference, meaning the FULL simulation predicted more rainfall in this region. The surplus was in the region where the AFRICA0 surface convergence was
consistently stronger than the FULL surface convergence. Also, the upper-level divergence was stronger for the AFRICA0 simulation than for the FULL simulation in this region. This may have been due to the difference in latent heating between the two simulations, leading to differences in the 300 hPa height and velocity fields. The combined effect of stronger convergence at low levels and stronger divergence at upper levels would help increase the vertical ascent of parcels in this region. Also, the difference in the characteristics of the air parcels arriving over this region would explain the rainfall differences. This will be discussed in the next section.

The ZERO simulation showed a north-south orientation in the rainfall distribution with a maximum of only 75 mm (Fig. 3.23c). With no mountains to create convergence or focus the airflow, extended rainfall over the same region did not occur. Differences in the rainfall show that for the most part, the ZERO simulation underestimated the rainfall relative to the FULL simulation (Fig 3.24b). However, there was an isolated positive difference of 60 mm in the western part of Italy just west of the 10°E meridian. A possible reason for this difference could be stronger upper-level divergence for the ZERO simulation as compared to the FULL simulation. Other reasons for the positive difference will also be discussed in the next section.

When compared to the observed rainfall, the model simulations agreed fairly well with the placement of the maximum in both the FULL and AFRICA0 simulations, near the LMTA. Also, the highest model accumulated rainfall is reasonable compared to the observations. The maxima along the Alpine slopes are also representative of the observations. Near the Italian coast, the model also estimated accumulations well. Overall, the FULL and AFRICA0 simulations appeared to simulate the rainfall reasonably well.
3.5.7 Model vertical cross sections

To see the vertical structure of the model atmosphere where the rainfall occurred, a cross section was taken across the Alps, near the maximum rainfall areas near the LMTA. This cross section would show the vertical motion patterns and also aid in determining the potential vorticity (PV) distribution across the heavy rainfall area. The PV would be analyzed to see if there was any upper troposphere and lower troposphere exchange and to show the areas of convection and latent heat release.

The cross sections for all three simulations are shown in Fig. 3.25 and the locations of the cross sections are shown in Fig. 3.22. For the FULL cross section, PV could be seen along the western slopes of the Alps and was associated with the rainfall seen at 0000 UTC 20 in Fig. 3.22. Also, the circulation vectors showed a circulation with the low-level flow from the east, rising along the western Alps, with a return flow to the east. This circulation was a thermally direct circulation, which is associated with the entrance region of a balanced upper-level jet (The entrance region was located in the upper left region of the cross section). Throughout the period between 0000 UTC and 1200 UTC 20, PV and rising motion associated with the rainfall were located near the western Alps. However, there was not a clear link between the upper-level PV (above 300 hPa) and the PV associated with the convection.

The AFRICA0 cross section showed more PV over the Alps than did the FULL cross section, corroborating the increase in rainfall seen with the AFRICA0 simulation (see Fig. 3.24). This shift to the west of the convection was consistent with the westward shift of the high $\theta_e$ tongue in the AFRICA0 simulation. The circulation pattern was similar to the FULL simulation. At 0600 UTC, the PV associated with the convection had reached up to 300 hPa,
indicating stronger convection. By 1200 UTC, there was a link between the upper-level and low-level PV patterns.

In the ZERO simulated cross section, PV was located to the west of the location of the Alps between 0 and 200 km on the cross section. This is the region where rainfall developed in the ZERO simulation. Throughout the twelve hour period from 0000 UTC to 1200 UTC, the PV was mainly located in this area. Also, upward motion was not as strong as in the other simulations, providing evidence of the importance of the mountains in triggering upward motion.

3.5.8 Trajectory analyses

Several features among the three simulations have been compared to show the differences resulting from the terrain configurations. In addition to these analyses, backward in time trajectories can show how the terrain configuration of the model affects the origin of air parcels that were over the LMTA. In order to more clearly examine the effects of the African terrain and overall model domain terrain on the airflow, twelve backward in time trajectories (hereafter referred to as back trajectories) were calculated from the concave region of the Alps.

The locations of the trajectory starting points are shown in Fig. 3.11. The points are along two rows, six points on each row (y=47 and 46) with each point two Δx's apart (between x=40 and 50) and one Δy apart. The location of these trajectories corresponded to locations in the region of heavy rainfall. However, for the sake of brevity, only the six most western trajectories will be discussed (points 1, 2, 3, 7, 8, and 9 in Fig. 3.11c).
The time frame of the trajectories was chosen based on radar and model rainfall data. The start time was chosen to be 1200 UTC 20 September, near the end of heavy rainfall. The trajectories were calculated back in time 36 hours to model initialization, 0000 UTC 19 September. Trajectories were calculated with an initial level of 850 hPa. In addition to calculating the trajectories, trajectory diagnostics were calculated to get an idea of the parcel characteristics. Diagnostics that will be discussed are equivalent potential temperature, potential temperature, mixing ratio, parcel height, and parcel temperature.

3.5.8.1 850 hPa back trajectories

Trajectories 1, 2, 3, 7, 8, and 9 and their associated diagnostics are shown in Figs. 3.26-31 respectively. Table 3.1 shows the 3-hourly and average distance between the trajectories for the FULL, AFRICA0, and ZERO simulations for each of the six trajectories.

In Fig. 3.26, the origin of parcels over the LMTA ranged from northern Algeria (FULL and ZERO) to the east coast of Tunisia near the Gulf of Gabo (AFRICA0). The FULL and ZERO trajectories followed the LLJ closely while the AFRICA0 trajectory traveled northeast then made a turn to the northwest 18-21 hours into the simulation. From Table 3.1, it can be seen that the ZERO simulated trajectory never deviated more than 206 km from the FULL trajectory while the AFRICA0 simulated trajectory was as far as almost 700 km from the FULL trajectory (forecast hour 3) when the FULL trajectory was traveling north and the AFRICA0 trajectory traveled northeast. It can also be seen that the ZERO trajectory was very close, on the average, to the FULL trajectory, i.e., 114.9 km. This was somewhat surprising since the ZERO simulation had no terrain to modify the airflow as in the FULL simulation. Both trajectories were linked closely to the low-level trough.
The diagnostics also reveal differences in the characteristics of the air parcels associated with the trajectories. In Fig. 3.26, it can be seen that the FULL simulated trajectory started at the highest height, just over 1 km while the AFRICA0 and ZERO trajectories stayed below 500 m until 0300 UTC 20 September (forecast hour 27). The upward motion near the mountains can be seen around forecast hour 33 (0900 UTC 20 September) as the parcels rose to around 1.4 km. From Fig. 3.26a, this is the time all three trajectories approached the coast. The parcel temperature profiles reflect the vertical movement of the parcels, as the temperature increased or decreased as the parcel descended or ascended. The parcels started out fairly warm, as to be expected since they originated in Africa. The equivalent potential temperature profiles and mixing ratio profiles were strongly correlated as the profiles were nearly identical in shape with the AFRICA0 trajectory having the highest $\theta_e$ and mixing ratio of the three trajectories, thus indicative of tropical air mass origin. Examining the potential temperature and height profiles and the lapse rate of potential temperature of the three simulated parcels show that the AFRICA0 trajectory exhibited more static instability than the FULL and ZERO trajectories. Also, examining the vertical velocities of the parcels (not shown) show that in the key 12 hour period from 0000 UTC - 1200 UTC 20, the AFRICA0 parcel exhibited stronger ascent, especially at 1200 UTC 20 (13 cm s$^{-1}$ for FULL, 24 cm s$^{-1}$ for AFRICA0, and 8 cm s$^{-1}$ for ZERO). The instability, mixing ratio, and vertical velocity of the AFRICA0 parcel for Point 1 would aid in explaining the higher rainfall totals for the AFRICA0 simulation.

The trajectories for Point 2 were also different in origin (Fig. 3.27a). While the AFRICA0 and ZERO trajectories originated in the Gulf of Gabo, the FULL trajectory originated in Sicily, suggesting the FULL parcel was slower in speed than the others. On the
average, the AFRICA0 and ZERO trajectories were about the same distance from the FULL trajectory, 303 and 337 km (Table 3.1). The slower wind speed of the FULL trajectory can be explained by the parcel height time series (Fig. 3.27b). The FULL trajectory is the lowest and never gets above 1 km until 0900 UTC 20 September (forecast hour 33). The AFRICA0 and ZERO trajectories descend throughout the time period until 0600 UTC 20 September (forecast hour 30). Once again, the $\theta_e$ and mixing ratio time series correlate well, again suggesting high $\theta_e$ values were due to moisture content. Note that the FULL trajectory has the highest $\theta_e$ and mixing ratio up to hour 24, since it is the lowest vertically, but then the ZERO trajectory is almost the same while the AFRICA0 remains low. The change occurs when the ZERO trajectory is near the northern tip of Tunisia, near Cape Bon and the FULL trajectory is in the Tyrrhenian Sea. Parcel temperatures show that the parcels initially warmed until between the 12th and 24th forecast hours and then began to cool as they ascended to 850 hPa with the ZERO parcel temperatures being the warmest and then after the 24th hour, the AFRICA0 became the warmest. Lapse rates of potential temperature for the parcels showed that the AFRICA0 parcel was the most statically unstable.

Point 3 trajectories exhibited interesting behavior (Fig. 3.28a). The FULL trajectory basically traveled north-northwest to Italy from the Libyan coast. The AFRICA0 trajectory initially traveled almost due east until the 21st hour (2100 UTC 19 September) and then made a sharp turn to the north as the parcel descended (Fig 3.28a). The ZERO trajectory originated from the Libyan coast, 383 km southeast of the FULL trajectory origin (Table 3.1) and initially was slow (as indicated by the closeness of the 3 hourly arrows) then accelerated around 0000 UTC 20 September. Overall, the AFRICA0 trajectory was closest to the FULL trajectory relative to the ZERO trajectory by about 70 km (Table 3.1).
Parcel height time series show that the AFRICA0 trajectory, starting from just over 2.5 km, steadily descended until 0600 UTC 20. The other two trajectories remained under 1 km until about 0900 UTC 20. The parcel temperature time series also indicates the steady descent by the AFRICA0 trajectory as the parcel warmed during its travel. The ZERO parcel was warm, over 20°C and also had the highest $\theta_e$ and mixing ratio values until 0300 UTC 20 when the FULL trajectory made a large increase in $\theta_e$ and mixing ratio when it was near Sicily. During the last 12 hours of the trajectory, coincident with the heaviest rainfalls, the AFRICA0 trajectory remained the most unstable.

Point 7 trajectories exhibit the most difference in origin locations (Fig. 3.29). Both the FULL and ZERO trajectories originated over Morocco and were strongly collocated with the low-level trough, while the AFRICA0 trajectory originated over 1,400 km away in Tunisia. This trajectory appeared to be in the flow ahead of the trough. Discussion of reasons for this large distance in origins will be discussed later in this section.

There was also a large difference in the height time series of these trajectories. The FULL trajectory was below 1 km throughout the time period until the last six hours while the other two trajectories showed a steady descent, especially the AFRICA0 trajectory. The AFRICA0 trajectory's mixing ratio reflected this descent as the parcel appeared to dry out as it descended (Fig. 3.29e). As with the other trajectories, the AFRICA0 parcel was the most unstable.

Simulated trajectories for Point 8 (Fig 3.30.) originated in roughly the same region with the ZERO trajectory being the farthest from the FULL trajectory (Table 3.1). The AFRICA0 trajectory remained closest to the FULL trajectory path. The FULL trajectory initially traveled northeast then turned to the northwest toward Italy while the AFRICA0 trajectory
traveled east-southeast then northwest, as did the FULL trajectory. The ZERO trajectory traveled northwest then north. The parcel height time series showed that the FULL parcel never ascended much over 500 m until hour 33 (0900 UTC 20). The other two parcels made a steady descent from their initial positions then ascended toward the 850 hPa level. Temperature time series showed that the FULL parcel remained within a 5°C range while the ZERO parcel warmed from about 17.5°C to over 25°C in about 15 hours even though it was the highest parcel. As with the other trajectories, the correlation between the equivalent potential temperature and mixing ratio was high, with the FULL parcel having the highest $\theta_e$ and mixing ratio values. Unlike the other trajectories, the FULL parcel for Point 8 was the most unstable.

Trajectory origins for Point 9 (Fig 3.31a) were similar in location as those of Point 8 and also appeared to take similar paths as those for Point 8. Height time series showed that the FULL and AFRICA0 trajectories descended from 1.5 and 2.25 km respectively to just over 500 m and 1 km respectively. They then ascended, as the other trajectories had done. Parcel temperatures agreed with the height time series for the most part in that the lower parcels (ZERO trajectory) had the highest temperatures as the ZERO parcel approached 30°C. The ZERO parcel equivalent potential temperature remained fairly constant from 0 to hour 6 and between hour 9 and 30, when it slightly increased. The AFRICA0 parcel remained fairly constant throughout the 36-hour period, around 325-326 K. The FULL parcel $\theta_e$ profile was constant from hour 0 to hour 18, slightly decreased to hour 21, and then rose by about 12 K from hour 21 to hour 30, when it once again decreased. The mixing ratio profiles were also very similar, giving evidence of the warm moist air coming from the African coastal regions. In terms of static stability, the ZERO parcel tended to be the most unstable.
By comparing the parcel diagnostics, we can infer some possible reasons for the higher rainfall totals in the western Alps with the AFRICA0 simulation. In addition to the low-level convergence and upper-level divergence patterns that aided in the increased rainfall for the AFRICA0 simulation, for four of the six trajectories discussed, the AFRICA0 parcels tended to be the most unstable ($d\theta/dz < 0$). Therefore, those parcels were more likely to be associated with moist convection and ascend. The combination of the stronger convergence/divergence and stability were key to the larger precipitation accumulations for the AFRICA0 simulation.

3.5.8.2 Time evolution of point 7 trajectories

Of the six trajectories, the trajectories from Point 7 exhibited the greatest average distance between the three simulated trajectories (Table 3.1). To determine reasons for the different paths taken by the simulated parcels, a detailed analysis of each 3-hourly position for each of the trajectories was done. The analyses began at 1200 UTC 20 and went back in time to 0300 UTC 20 since the trajectories were back trajectories. The position of the parcel and the winds at the model $\sigma$ level at which the parcel was located vertically were plotted.

The detailed trajectory analyses for the FULL, AFRICA0, and ZERO simulations are shown in Fig. 3.32. From a large scale perspective, the flow patterns for the three simulations were very similar even though the parcels were located at different vertical levels. From Fig 3.32, it can be seen that the trajectories diverged from one another between 1200 UTC and 0900 UTC 20. At the initial time of the trajectories, the FULL and ZERO simulations show a south-southwesterly wind (wind directions of 203° and 198° respectively)
at the parcel location (Fig. 3.32a, e). In the AFRICA0 simulation, the wind direction for the location of the parcel was almost southerly (185°) (Fig. 3.32c).

At 0900 UTC, the FULL and ZERO parcels were southwest of the initial position and the AFRICA0 parcel was southeast of the initial position. At this time, the FULL and ZERO parcels were only 24 km apart while the AFRICA0 parcel was 121 km from the FULL parcel after only three hours. At this time, the AFRICA0 parcel was embedded in a southeasterly flow, leading to an origin along the Tunisian coast (Fig. 3.32d). Meanwhile, the parcels for the other two simulations were embedded in the southwesterly flow of the trough leading to origins in Morocco. It can be seen from the figures, that a subtle difference in wind direction can lead to vastly different trajectories by placing parcels in two completely different airstreams. This finding shows how the African terrain affects conditions upstream in the flow field.

These findings explain the differences between the FULL and AFRICA0 simulations and how the Atlas Mountains can affect the flow toward the Alps. However, another question arises: why are the FULL and ZERO trajectories so similar? If the absence of terrain in Africa can lead to such a different trajectory, why doesn't the complete lack of terrain lead to another vastly different trajectory? As previously noted, at 0900 UTC 20, the FULL and ZERO parcels were embedded in the southwesterly flow of the trough. For the most part, between 0000 UTC 19 and 1200 UTC 20, the parcels were located over the Mediterranean where terrain effects were negligible. With the exception of some subtle differences in the winds, the two parcels flowed back to the same general location.

The reasoning for the different trajectory by the AFRICA0 simulation is that the southeasterly wind direction at the parcel location was just enough to put the parcel in the
southeasterly flow that was ahead of the trough, which was evident in all three simulations, and, therefore, transporting the parcel back to Tunisia. Also, once the parcels began moving in different directions and at different levels, the parcel characteristics also changed, affecting the rainfall development over the Alps.

3.6 Summary and conclusions

From observations and model results, the factors often associated with Alpine rainfall events came into play in IOP-2B. A low-level jet transported warm moist air from the south that impinged upon the Alps, was lifted when it impinged, and led to precipitation formation. A low-level convergence zone formed in the LMTA as the southerly low-level winds converged with southeasterly and easterly winds that flowed in from the Adriatic Sea. Upper-level divergence also supported the low-level convergence in aiding the ascent of air parcels over the LMTA. Between 0000 UTC and 1200 UTC 20, the upper-level jet entrance associated with the trough was located just west of the LMTA. Consistent with the upper-level ageostrophic transverse circulations of the jet entrance region, a circulation was created in which air flowed from the east and ascended over the LMTA. These features, the LLJ, the Alps, the juxtaposition of low-level convergence and upper-level divergence, and the upper-level jet entrance were key ingredients in forming the precipitation.

Sensitivity tests of the African terrain showed that the Atlas Mountains modified the airflow such that the rainfall over the LMTA was increased. Changing the North African terrain changed the location of the origin of air parcels that were located over the LMTA by hundreds of kilometers and also changed the characteristics of the air parcels. Also, changing the North African terrain shifted the tongue of high $\theta_e$ air westward relative to the
FULL simulation, leading to a shift in the convection and higher rainfall totals to the west. These findings show that the Atlas Mountains do play a role in the precipitation distribution over the Alps.

Removing all terrain, including the Alps, showed the importance of the Alps in the rainfall of IOP-2B. Without the Alps, the low-level convergence zone was markedly underdeveloped and rainfall accumulations were moderate. Without the Alps, the southeasterly flow from the Adriatic was not blocked and allowed to turn west, to create the primary convergence zone.

Future work can involve other sensitivity tests of terrain such as the mountains of Spain and France that may have helped funnel the northwest winds around the trough to help create convergence and rainfall just west of the LMTA. Also important, but not studied in this research, are the sea surface temperatures of the Mediterranean Sea. Warming or cooling the SSTs in the model may affect the flow, change the static energy of air parcels being lifted, and therefore lead to changes in the rainfall distribution. Another test will be to perform sensitivity tests of the boundary layer by removing or modifying the elevated hot air transported from North Africa. This would affect the characteristics of the air being transported toward the Alps and possibly change the convection in the LMTA.
Table 3.1. 3-hourly distances (km) between FULL and AFRICA0 trajectories (F-A) and between FULL and ZERO trajectories (F-Z) from 1200 UTC 20 back to 0000 UTC 19 September 1999. Average distance over the 36 hour period is also given.

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Figure 3.1. Past Alpine rainfall events with MM5 derived terrain every 500 m.
Figure 3.2. Subjective surface analyses for a) 0000 UTC 19, b) 0000 UTC 20, c) 0600 UTC 20, and d) 1200 UTC 20 September. Station plots are standard with temperature and dew-point to left of station (upper and lower left respectively) and sea level pressure to upper right in hPa. Wind shaft indicates direction wind is coming from. A half barb is equal to 5 m s\(^{-1}\), a full barb equals 10 m s\(^{-1}\) and a pennant equals 50 m s\(^{-1}\). Temperatures are in Celsius.
Figure 3.2. Continued.
Figure 3.3. Subjective height analyses at a) 850 hPa and b) 300 hPa for 0000 UTC 19 September. Heights in meters are plotted to right of wind barb and temperatures to left. Winds are in m s$^{-1}$ with the wind barb convention following that of Fig. 3.2. For a) height contours are every 30 dam and for b) every 60 dam.
Figure 3.4. As for Fig. 3.3 except for 0000 UTC 20 September.
Figure 3.5. As for Fig. 3.3 except for 1200 UTC 20 September.
Figure 3.6. Observed soundings for a) 1200 UTC 19 Cagliari, Sardinia b) 0000 UTC 20 Cagliari, c) 0000 UTC 20 Milan, Italy and d) 1200 UTC Milan. Temperature and dew-point are represented by heavy solid lines. Adiabats are represented by short dashed lines, pseudo-adiabats by medium dash lines, and mixing ratios represented by short and medium dashed lines. Winds are in m s$^{-1}$ with the wind barb convention the same as Fig. 3.2. Temperatures are in Celsius.
Figure 3.7. Alpine radar composite rainfall rates (mm h$^{-1}$) for a) 0000 UTC 19 September, b) 0000 UTC 20 September, c) 0600 UTC 20 September, and d) 1200 UTC 20 September 1999.
Figure 3.8. Observed 48-hour accumulated rainfall (mm) for the period 0000 UTC 19 - 0000 UTC 21 September. Approximate location of Lago Maggiore is denoted by black dot.
Figure 3.9. Infrared radar imagery for a) 0130 UTC 19 September, b) 0130 UTC 20 September, c) 0600 UTC 20 September, and d) 1200 UTC 20 September.
Figure 3.10. Water vapor satellite imagery for a) 0200 UTC 19 September, b) 0200 UTC 20 September, c) 0600 UTC 20 September and d) 1200 UTC 20 September.
Figure 3.11. a) Model area and domains. Domains 1, 2, and 3 are 45, 15, and 5 km resolution respectively. b) Domain 1 terrain every 500 m, c) back trajectory starting points and 1,000 m terrain contour (heavy solid line), and d) model terrain of North Africa for FULL simulation.
Figure 3.11. Continued.
Figure 3.12. 20 September Domain 1 sea level pressure (every 4 hPa) and winds (m s$^{-1}$). Panels a-c are FULL, d-f are AFRICA0, and panels g-i are ZERO. Times are given in lower right corners. A half barb equals 5 m s$^{-1}$, a full barb equals 10 m s$^{-1}$ and a pennant equals 50 m s$^{-1}$.
Figure 3.12. Continued.
Figure 3.13. As for Fig. 3.12 except for Domain 1 850 hPa heights (every 30 m), isotachs (m s\(^{-1}\)), and winds. Wind speeds greater than 20 m s\(^{-1}\) are shaded.
Figure 3.13. Continued.
Figure 3.14. As for Fig. 3.13 except for Domain 1 850 hPa equivalent potential temperature (every 8 K).
Figure 3.14. Continued.
Figure 3.15. As for Fig. 3.13 except for Domain 1 850 hPa relative humidity (> 70% shaded) and winds.
Figure 3.15. Continued.
Figure 3.16. FULL Domain 1 300 hPa heights (every 60 m), isotachs (every 10 m s$^{-1}$), and winds (m s$^{-1}$) for a) 0000 UTC 19, b) 0000 UTC 20, c) 0600 UTC 20 and d) 1200 UTC 20. Wind speeds greater than 40 m s$^{-1}$ are shaded. Wind barb convention follows Fig. 3.12.
Figure 3.17. 20 September FULL Domain 1 surface velocity convergence (every $5 \times 10^5$ s$^{-1}$) for a) 0000 UTC, b) 0600 UTC, and c) 1200 UTC. 300 hPa velocity divergence (every $10^5$ s$^{-1}$) and 700 hPa vertical velocity ($> 5$ cm s$^{-1}$ shaded) for d) 0000 UTC, e) 0600 UTC, and f) 1200 UTC. 1 km terrain elevation denoted by solid heavy line in a-c and dashed line in d-f.
Figure 3.18. As for Fig. 3.17 except for AFRICA0 Domain 1.
Figure 3.19. As for Fig. 3.17 except for ZERO Domain 1.
Figure 3.20. Model soundings for Cagliari, Sardinia for a) FULL 1200 UTC 19, b) FULL 0000 UTC 20, c) AFRICA0 1200 UTC 19, d) AFRICA0 0000 UTC 20, e) ZERO 1200 UTC 19, and f) ZERO 0000 UTC 20 September. Temperature and dew-point profiles represented by heavy solid lines. Parcel temperature profile is represented by heavy dashed lines. Adiabats represented by dotted lines, pseudoadiabats represented by light curving dashed lines and mixing ratios denoted by straight dashed lines below 700 hPa. Temperatures are in Celsius and winds in m s\(^{-1}\). Wind barbs follow convention of Fig. 3.12.
Figure 3.21. As for Fig. 3.20 except for Milan Italy for a) FULL 0000 UTC 20, b) FULL 1200 UTC 20, c) AFRICA0 0000 UTC 20, d) AFRICA0 1200 UTC 20, e) ZERO 0000 UTC 20, and f) ZERO 1200 UTC 20 September.
Figure 3.22. 20 September Domain 2 6-hour rainfall (every 20 mm) and surface winds (m s$^{-1}$) for a-c) FULL, d-f) AFRICA0, and g-i) ZERO. Heavy solid contour denotes 1 km terrain and solid straight line denotes location of cross section in Fig. 3.25. Wind barb convention is as described in Fig. 3.12 and times are listed in lower right corner of panels.
Figure 3.22. Continued.
Figure 3.22. Continued.
Figure 3.23. Simulated Domain 2 48-hour accumulated rainfall (mm) for a) FULL simulation, b) AFRICA0 simulation, and c) ZERO simulation. Accumulation time is same as in Fig. 3.8. Heavy dotted line in a and b is the 1 km terrain contour.
Figure 3.24. Domain 2 48-hour accumulated rainfall differences (every 15 mm) for a) AFRICA0 - FULL and b) ZERO - FULL. Positive differences are shaded. Negative differences denoted by dashed lines.
Figure 3.25. 20 September Domain 2 cross section AB shown in Fig. 3.22 for a-c) FULL, d-f) AFRICA0, and g-i) ZERO. Solid lines are potential temperature (every 2K), arrows represent ageostrophic circulation vectors, and shading represents potential vorticity (every 0.5 PVU. 1 PVU = $10^6$ m$^2$ s$^{-1}$ K kg$^{-1}$). Times are shown in lower right corners.
Figure 3.25. Continued.
Figure 3.25. Continued.
Figure 3.26. a) Domain 1 Point 1 36 hour back trajectories (0000 UTC 19 - 1200 UTC 20) for FULL (black), AFRICA0 (blue) and ZERO (green) simulations. Parcel diagnostics: b) parcel height (km), c) potential temperature (K), d) equivalent potential temperature (K), e) mixing ratio (g kg$^{-1}$) and f) parcel temperature. Black, blue, and green lines represent FULL, AFRICA0, and ZERO parcels respectively.
Figure 3.27. As for Fig. 3.26 except for Point 2.
Figure 3.28. As for Fig. 3.26 except for Point 3.
Figure 3.29. As for Fig. 3.26 except for Point 7.
Figure 3.30. As for Fig. 3.26 except for Point 8.
Figure 3.31. As for Fig. 3.26 except for Point 9.
Figure 3.32. Parcel positions and winds (m s\(^{-1}\)) at pressure level of parcels for the three simulated trajectories for Point 7 backward in time from 1200 UTC to 0300 UTC 20 September. Line in each panel denotes path of parcel back in time since 1200 UTC 20 and red dot signifies location of parcel at time indicated in each panel. The parcels' pressure levels at each time are also indicated in each panel. The top row of panels is the FULL trajectory (black), the middle row is the AFRICA0 trajectory (blue), and the bottom row is the ZERO trajectory (green). Wind barbs follow convention as in Fig. 3.12.