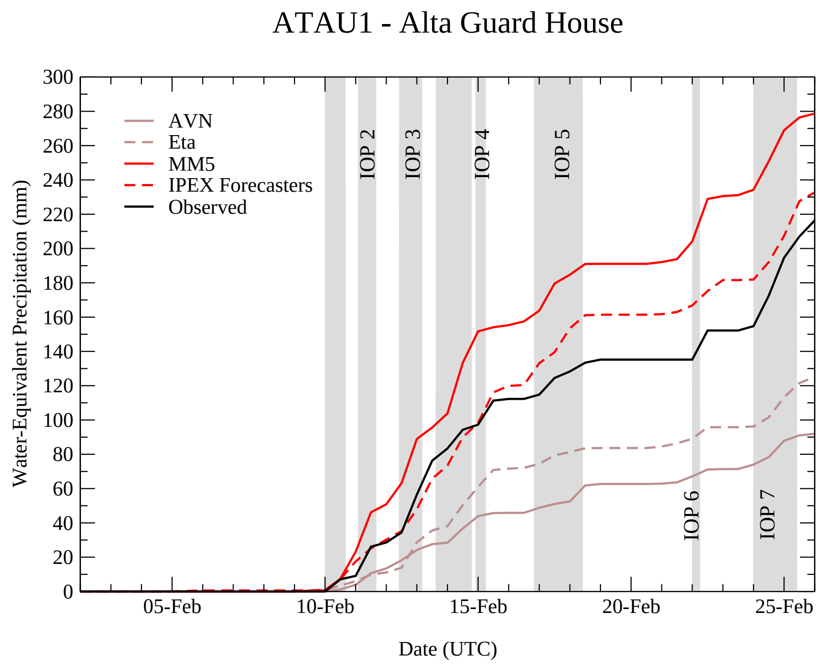
CHAPTER 5

VALIDATION OF QPF

Point Forecasts

The previous chapter described the different precipitation events that occurred during IPEX. This chapter will focus on the performance of the models during these events. To introduce the variation in model QPF skill as a function of location and model, model forecasts from the AVN, Eta, and MM5 at Alta Guard House (ATAU1), Ben Lomond Peak (BLPU1), Salt Lake International Airport (SLC), and Sandy (SNH) (Fig. 4.2) are evaluated against observed precipitation. Model QPF on the grids shown in Chapter 3 are interpolated to these four locations. The four points are representative of mountain and valley locations around the Salt Lake City area.

Figure 5.1 shows the cumulative time series of observed and forecast precipitation during the period 2-25 February at the four stations. Two of the stations, Alta (ATAU1) and Salt Lake airport (SLC), were point forecast sites for the IPEX forecast team, and their forecasts are also included for comparison. Model precipitation is accumulated from the 12-h forecasts valid 24 h after the 0000 and 1200 UTC initialization times. It is important to note that the forecast times used by the IPEX forecasters do not correspond exactly to the available model forecast times. Forecasts by the IPEX forecast team were made only once per day around 1800 UTC. Forecasts for the airport (SLC) were made for 6-h totals valid 6, 12, 18, and 24 h following 1800 UTC. Forecasts for Alta (ATAU1) were made in



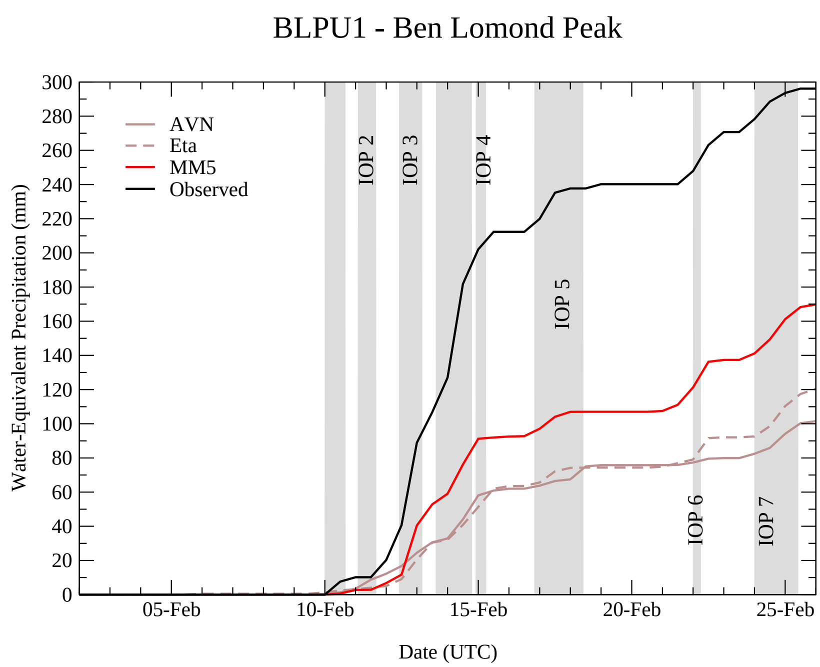
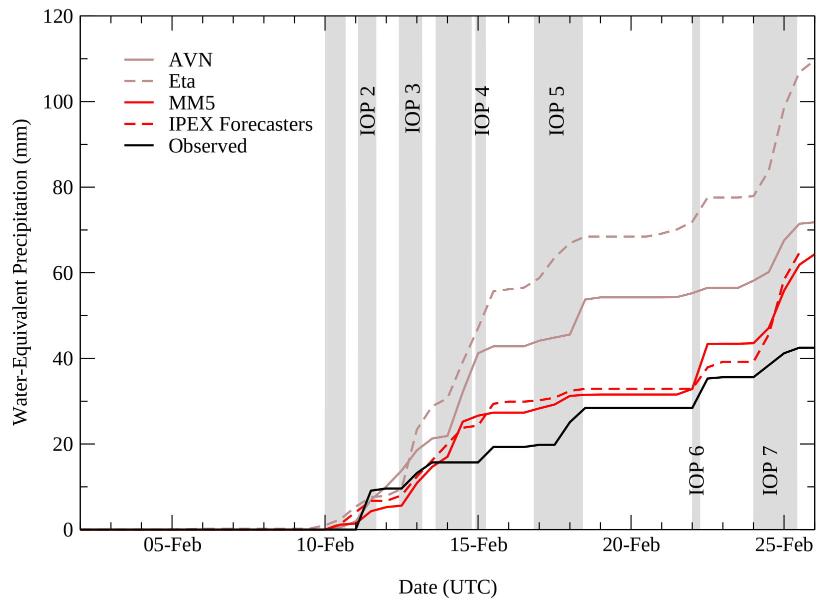


Figure 5.1. Cumulative time series of observed and forecast precipitation at four sites during IPEX. Shaded areas represent periods of subjectively-determined precipitation events over the IPEX domain, with the events corresponding to the IOPs labeled.

SLC - Salt Lake Airport



SNH - Sandy

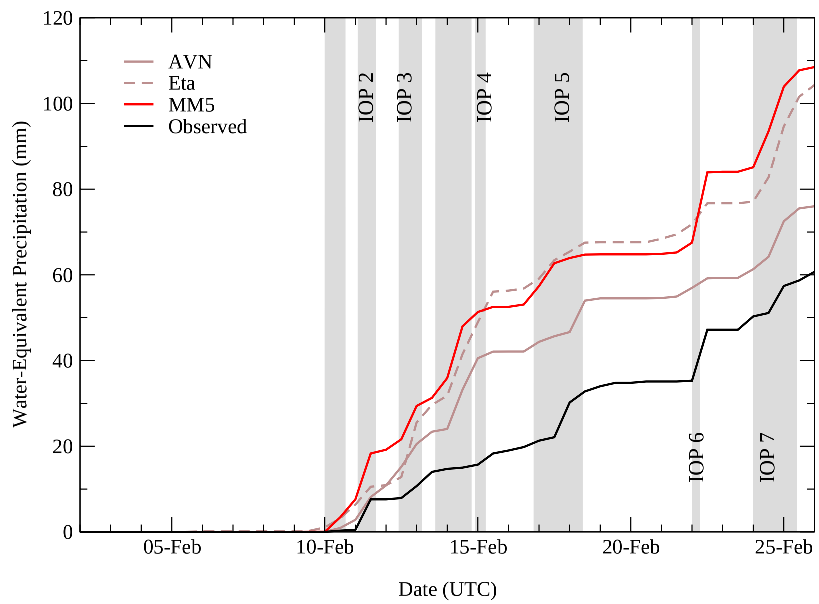


Figure 5.1. (Continued)

12-h increments to correspond to the 0000 and 1200 UTC reporting times of the station, and are thus valid 18 and 30 h from the 1800 UTC forecast time.

Focusing first on the forecast performance of the coarser-resolution models (AVN and Eta), it is apparent that both of these models underforecast the total precipitation at the high-elevation sites and overforecast precipitation at the lower-elevation sites. This general result was expected based upon prior QPF validation studies in mountainous terrain. Although the Eta model performed better than the AVN in the mountains, its cumulative error is larger than that of the AVN in the valleys. Overall, the Eta produced more precipitation than the AVN at all four locations during IPEX, a tendency which could be due in part to the larger height gradient of the Eta model's terrain.

The MM5 overpredicted the precipitation at Alta (ATAU1), even though it underforecast at Ben Lomond Peak (BLPU1). Most of the errors with the MM5 forecasts at both sites occurred in the first half of the month, during IOP 2 and the strong orographic events of IOP 3 and 14 February. The model appears to be more accurate in the mountains for the events after IOP 4. At the two valley sites, the MM5 overforecast the cumulative precipitation at both the airport (SLC) and Sandy (SNH). However, while the error is smaller at the airport (SLC), the model has a much larger error at Sandy (SNH). In fact, the cumulative total forecast by the MM5 at Sandy (SNH) exceeds that of both the AVN and Eta. This could be due to the station's proximity to the mountains. The location of Sandy (SNH) is on the slope of the model's Wasatch Mountains (Fig. 3.3), with its nearest grid point close to 500 m higher than the actual location of the station. On the other hand, the Salt Lake airport is clearly located in the model's valley, with all four surrounding grid points at low elevations. Comparing model performance for individual events, the MM5 does not always perform better than the coarser-resolution models, especially in the valleys. For example, the AVN appears to produce better forecasts for the IOP 7 event in the valleys, and both the AVN and Eta were better at predicting the total precipitation during the IOP 5 event than the MM5 at the airport (SLC).

Several other issues regarding model performance during IPEX are also evident from Fig. 5.1. For the event on 14 February, the models all forecast significant precipitation to occur in the mountains as well as in the valleys. Heavy precipitation was indeed reported at the two mountain sites, but no precipitation was observed at the airport (SLC) and very little at Sandy (SNH). Furthermore, for the squall line event of IOP 4, the models forecast either no change or a decrease in the precipitation rate as the system moved through. In reality, precipitation increased at all sites except Ben Lomond Peak (BLPU1). This could be due either to the inability of the models to separate the IOP 4 event from that which produced the precipitation on 14 February, or to the models overforecasting the rate of precipitation on 14 February and/or underforecasting the precipitation rate of the IOP 4 event. Errors in the timing of precipitation events are also evident in the model forecasts. At all of the sites except Ben Lomond Peak (BLPU1), all of the models forecast precipitation for IOP 6 to begin during the 12-h period prior to the time the precipitation band actually moved through.

Model forecasts are not expected to be perfect, so they should only be used for guidance by forecasters. It is expected that human forecasters would be able to improve upon model forecasts based on their knowledge of model performance and local effects. The added value of IPEX forecasters are examined at Alta (ATAU1) and the Salt Lake airport (SLC).

At Alta (ATAU1), the forecasters do improve upon the models. Their cumulative total for the entire period is much closer to that observed than any of the models. However, there are a couple of events where their forecasts were worse than the models' forecasts. For example, the forecasters have larger QPF errors for IOP 5 than the models, and they predicted the duration of the precipitation event during IOP 6 to be longer than it actually was.

At the airport (SLC), although the forecasters improve upon the AVN and Eta, their forecasts were similar to the totals forecast by the MM5. The IOP 4 event was predicted rather well by the forecast team, but they overforecast precipitation during 14 February. Furthermore, only light amounts of precipitation were forecast by the models to occur during the latter half of the day on 13 February, but the forecasters predicted heavier precipitation. Both the models and the forecast team were wrong in this case, since precipitation was not observed, but the error was larger for the forecasters. Another case where the forecast team fared worse than the models is the IOP 5 event, which was significantly underpredicted by the forecasters. Finally, as was the case at Alta (ATAU1), the IOP 6 event was forecast to last longer than observed.

As evident from the results of the point forecasts, the higher-resolution MM5 model produced better cumulative QPF for the IPEX period than the lower-resolution AVN or Eta. However, the MM5 did not always perform better than the other models during the individual events. There were some events when the lower-resolution models produced forecasts that were similar to or better than the MM5 forecasts. The value added by human forecasters appears to minimize some of the errors in the model forecasts, but there is still much room for improvement.

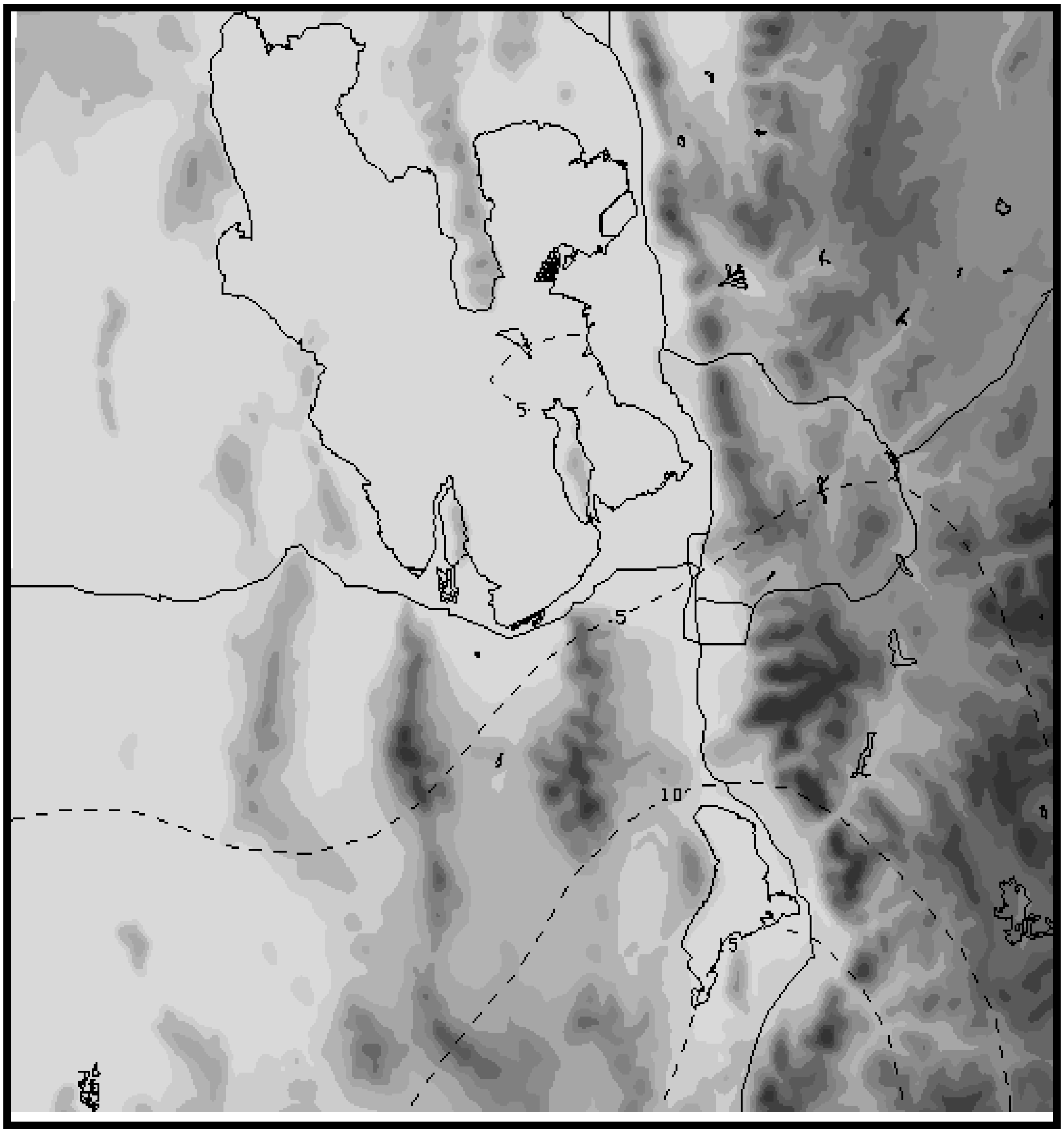
Model Spatial Distribution

The observed spatial distributions of quantitative precipitation during the IPEX IOPs were described in the previous chapter. It was shown that differing synoptic and mesoscale circulations led to precipitation totals that varied greatly over short distances. This section evaluates the performance of the three models described in Chapter 3 to forecast the distribution of precipitation during the IOPs.

Contour plots were created from the Eta and MM5 precipitation forecasts for each of the IOP periods depicted in the spatial maps in Chapter 4. The AVN was not used because very little spatial detail is evident due to the coarse resolution of the output grid. To keep the forecast range for each IOP as consistent as possible for meaningful comparisons, the 12-24-h forecast periods for the 0000 and 1200 UTC model runs are evaluated. Forecasts from successive model runs were combined to form the periods corresponding to the IOPs.

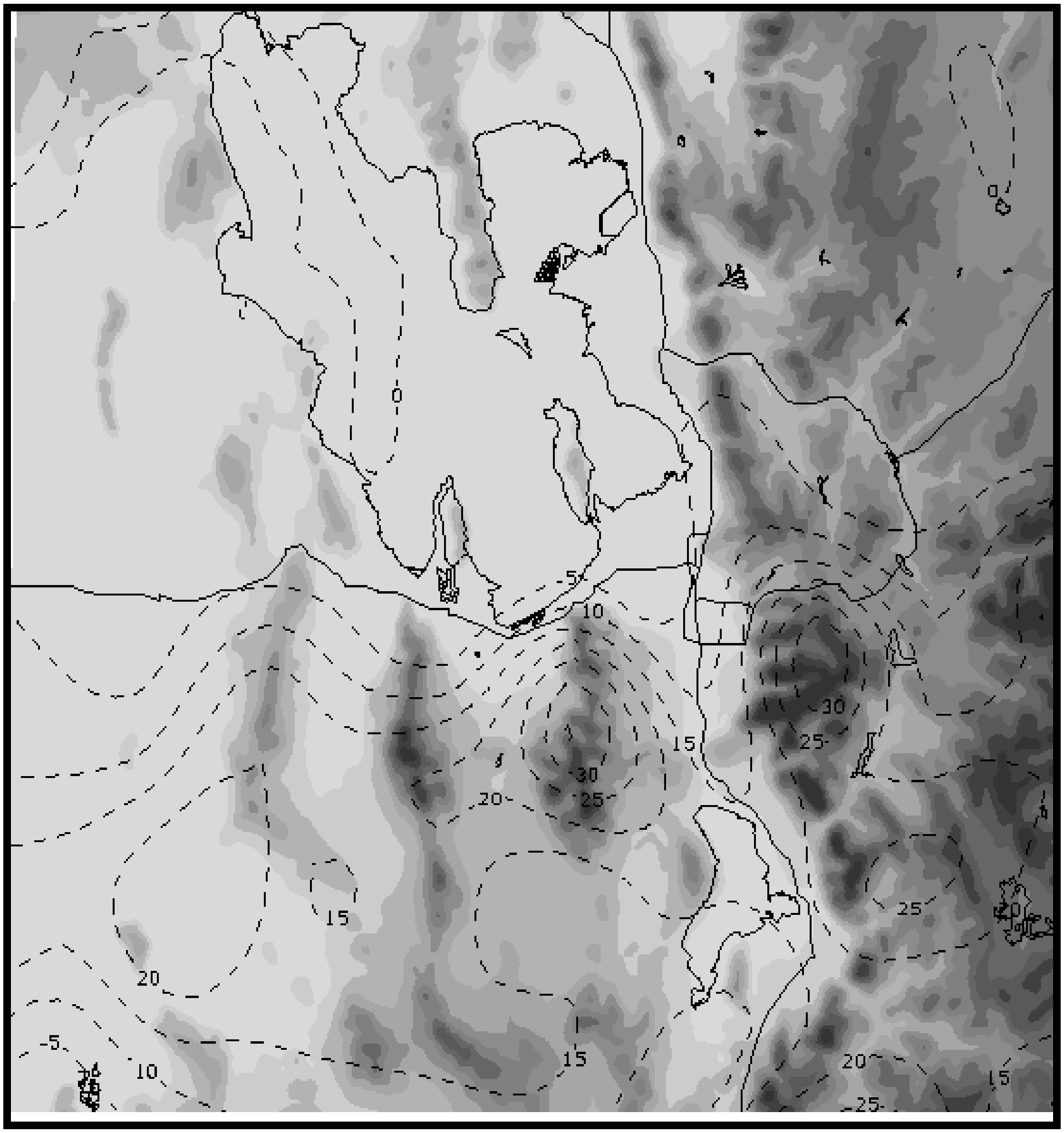
Contour maps of the model precipitation forecasts during IOP 2 are shown in Fig. 5.2. The Eta (Fig. 5.2a) captured the large-scale distribution of precipitation with the heaviest precipitation to the south. However, the Eta's maximum lies south of Provo, while the observed maximum (Fig. 4.4) is located in the mountains northeast of Provo. The model output grid does not resolve the terrain in enough detail to depict accurately the precipitation structure. Quantitative totals forecast by the Eta are only slightly less than observed throughout most of the area.

Like the Eta, the MM5 (Fig. 5.2b) also did a good job limiting most of the precipitation to the southern half of the region. Also noticeable is the strong orographic enhancement produced by the MM5. However, it overforecast the total over the Oquirrhs



(a)

Figure 5.2. Spatial map of the precipitation forecast for IOP 2 from the a) Eta and b) MM5. Contours are isohyets incremented every 5 mm.



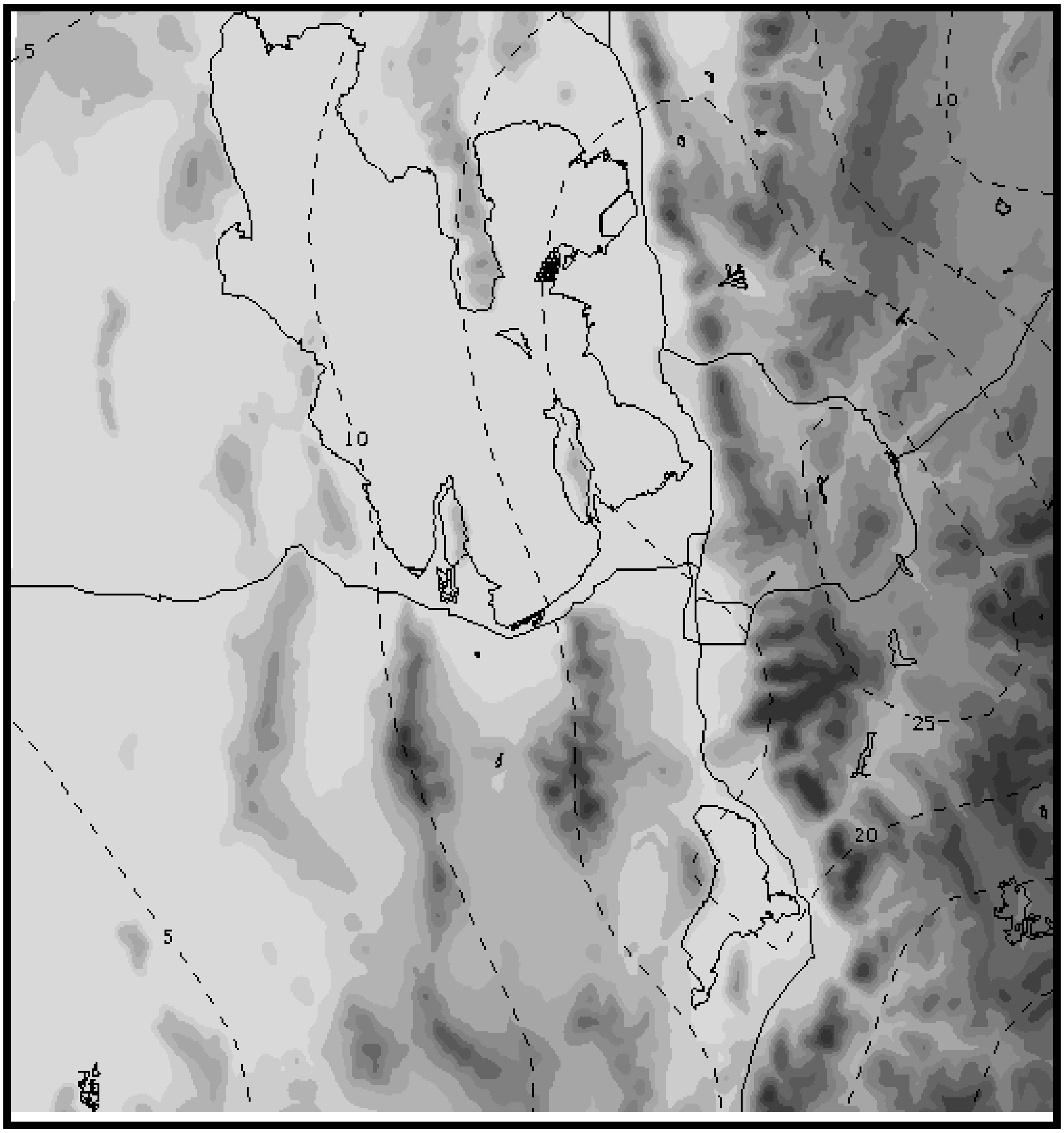
(b)

Figure 5.2. (Continued)

as well as in the Tooele Valley. Furthermore, the maximum in the southern Wasatch was placed in the Cottonwood Canyons area southeast of Salt Lake City, slightly north of the observed maximum. The location error can be attributed to the model topography. Since the model-resolved terrain (Fig. 3.3) has a local height maximum in the Cottonwoods area, it would be a favorable location for the model to produce heavy precipitation. The maximum value predicted by the model is greater than 30 mm, which corresponds to the observed maximum of 43 mm much better than the Eta.

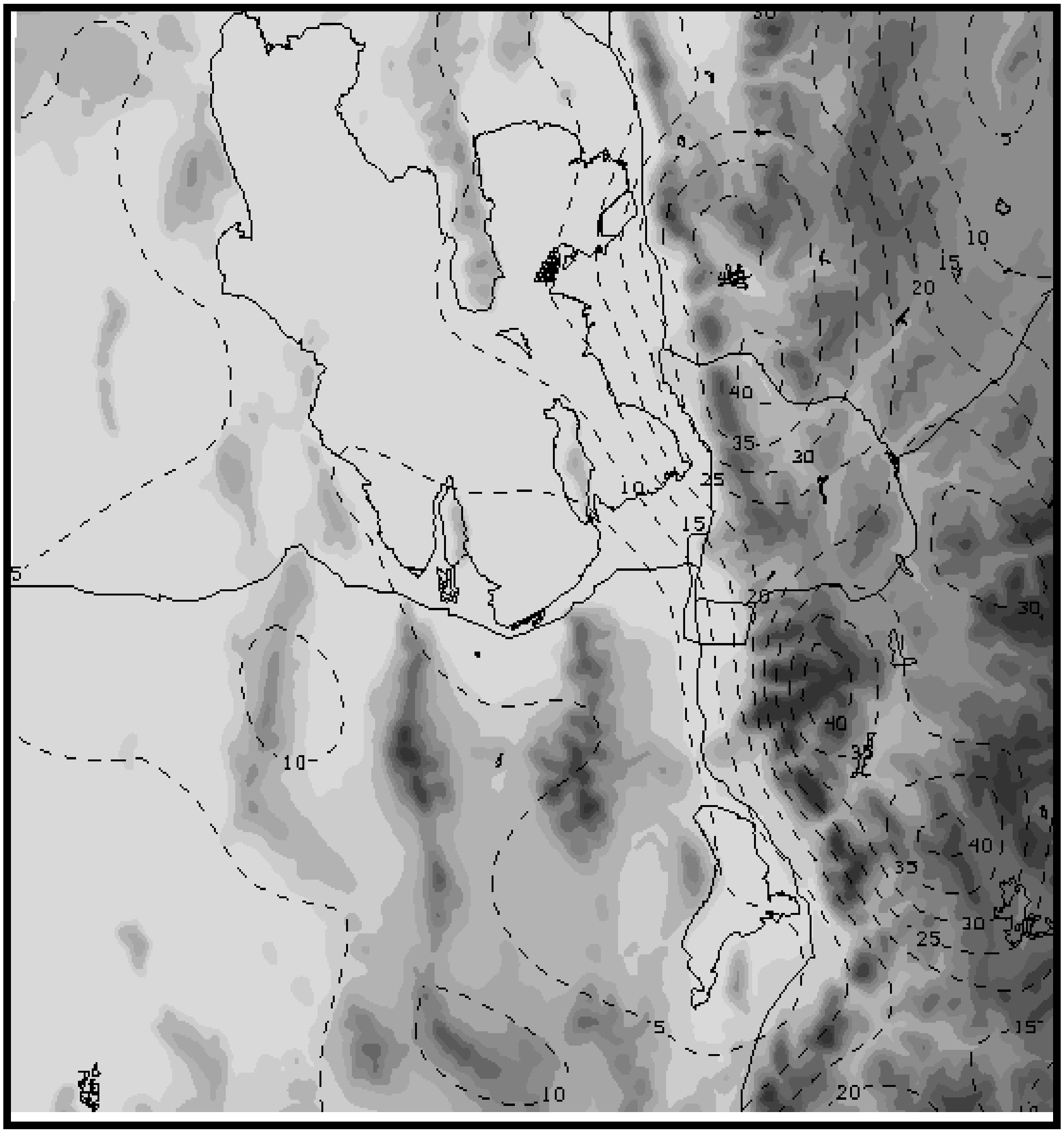
The precipitation forecasts for the strong orographic event of IOP 3 are shown in Fig. 5.3. The Eta model forecast (Fig. 5.3a) shows evidence of orographic effects with a gradient in precipitation that increases with increasingly higher model terrain. Totals greater than 20 mm were forecast to occur over the Wasatch Range, but those values are less than the 30-50 mm observed along most of the Wasatch crest (Fig. 4.7). The Eta placed the maximum to the lee of the crest, but this appears to be a consequence of the model's inability to resolve the narrow Wasatch crest (see Fig. 3.2).

A more complex distribution of precipitation is evident in the MM5 forecast (Fig. 5.3b). The model produced several local maxima of greater than 40 mm over the mountains. It was able to correctly place the maximum over the Cottonwoods area. The MM5's quantitative forecast in that area also verified well with the observations. The correct placement of this maximum is probably due to the existence of the local maximum in elevation of the model topography in that area. Another maximum was forecast to occur further to the southeast, but few observations exist in that area to verify the forecast. Two other maxima of greater than 40 mm were forecast to occur along the northern Wasatch, which verified well with the observations except that the model placed the centers slightly



(a)

Figure 5.3. Spatial map of the precipitation forecast for IOP 3 from the a) Eta and b) MM5. Contours are isohyets incremented every 5 mm.



(b)

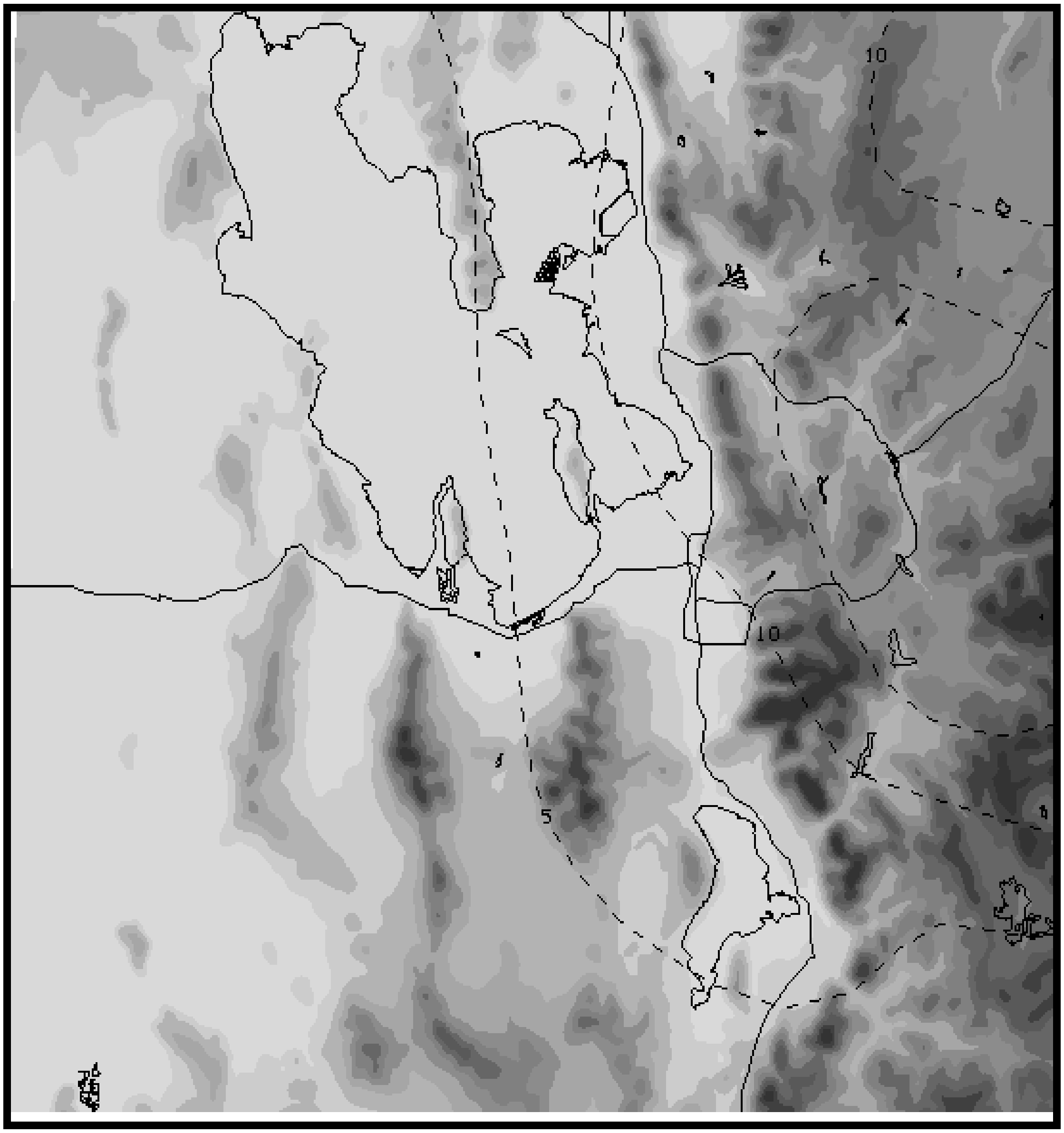
Figure 5.3. (Continued)

to the lee of the crest. Like the Eta, the placement of the model's maximum precipitation could be due to the narrow Wasatch crest not being well resolved by the MM5. Quantitatively, the model underforecast the large maxima observed in the northern Wasatch. Althouth the spatial distribution of precipitation was forecast well in the Wasatch, the model failed to forecast orographic enhancement over the Oquirrhs and Stansburys. In general, though, the MM5 forecast depicts a structure that is comparable to the observed distribution, with quantitative totals better predicted than the Eta model.

As depicted in Fig. 4.11, relatively low values of precipitation were observed in the valleys during the fast-moving squall line of IOP 4, with slight enhancement evident over the high-elevation sites. Figure 5.4 shows the model forecasts for this IOP. The Eta model (Fig. 5.4a) predicted the slight orographic enhancement in the precipitation distribution. However, the location of the maximum was shifted eastward to correspond to the model topography. The Eta's quantitative totals verify well with the observed, with maximum values in the 15-20-mm range at high elevations and less than 10 mm at lower elevations.

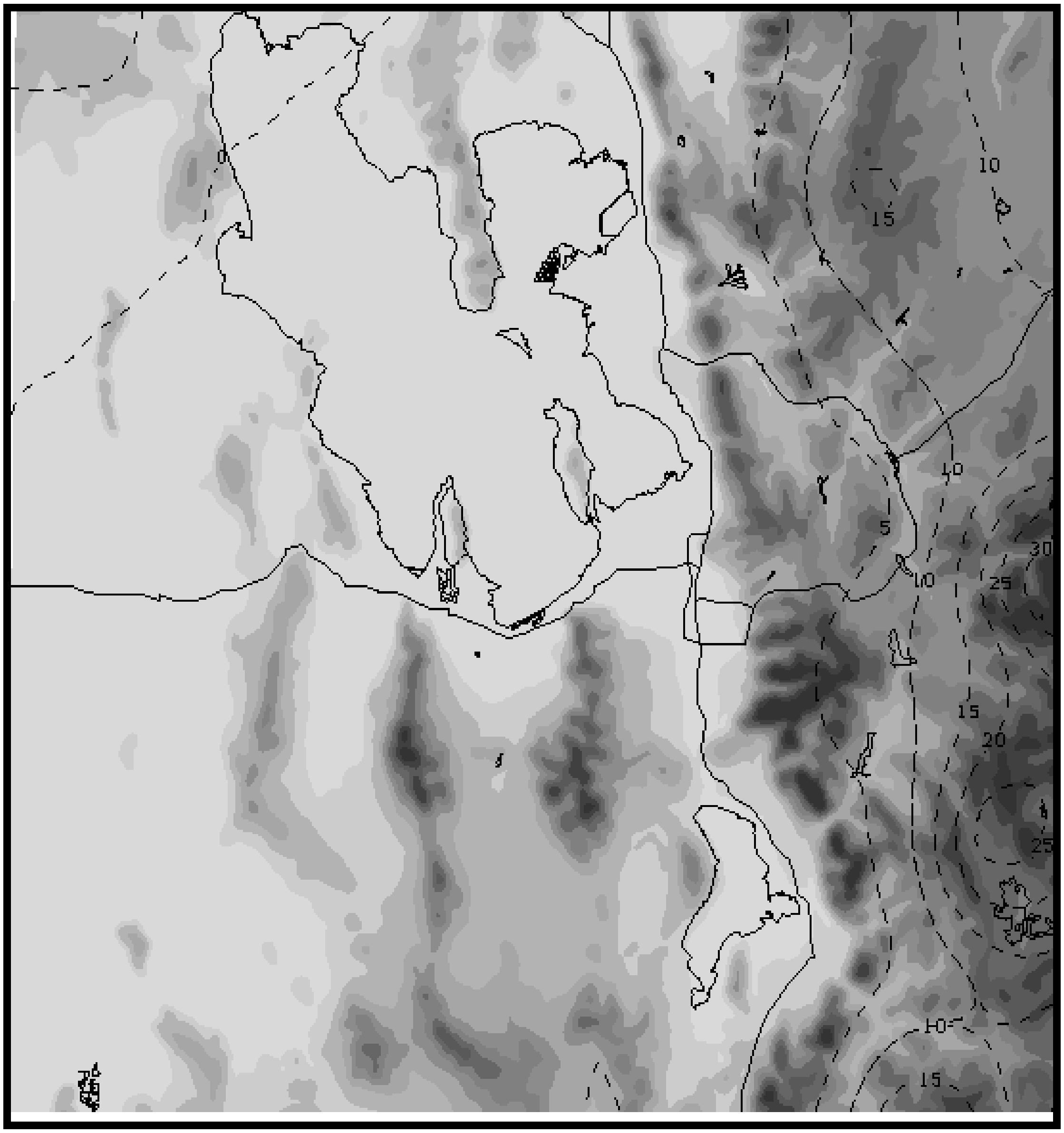
Like the Eta, the MM5 (Fig. 5.4b) forecast also shows evidence of orographic enhancement, but it failed to place the largest amounts over the Wasatch crest. Instead, it followed the model topography, placing the heaviest precipitation over the model's highest terrain well to the east of the Wasatch crest. The MM5's maximum exceeds 30 mm, which is larger than that reported at any of the available gauges. For this IOP, it appears that the Eta forecast is more accurate than the MM5.

The model forecasts for IOP 5 are shown in Fig. 5.5. Precipitation in the Eta forecast (Fig. 5.5a) is very evenly distributed, with a broad area of 5-10 mm of precipitation forecast over the Wasatch and the central part of the region. Forecast totals



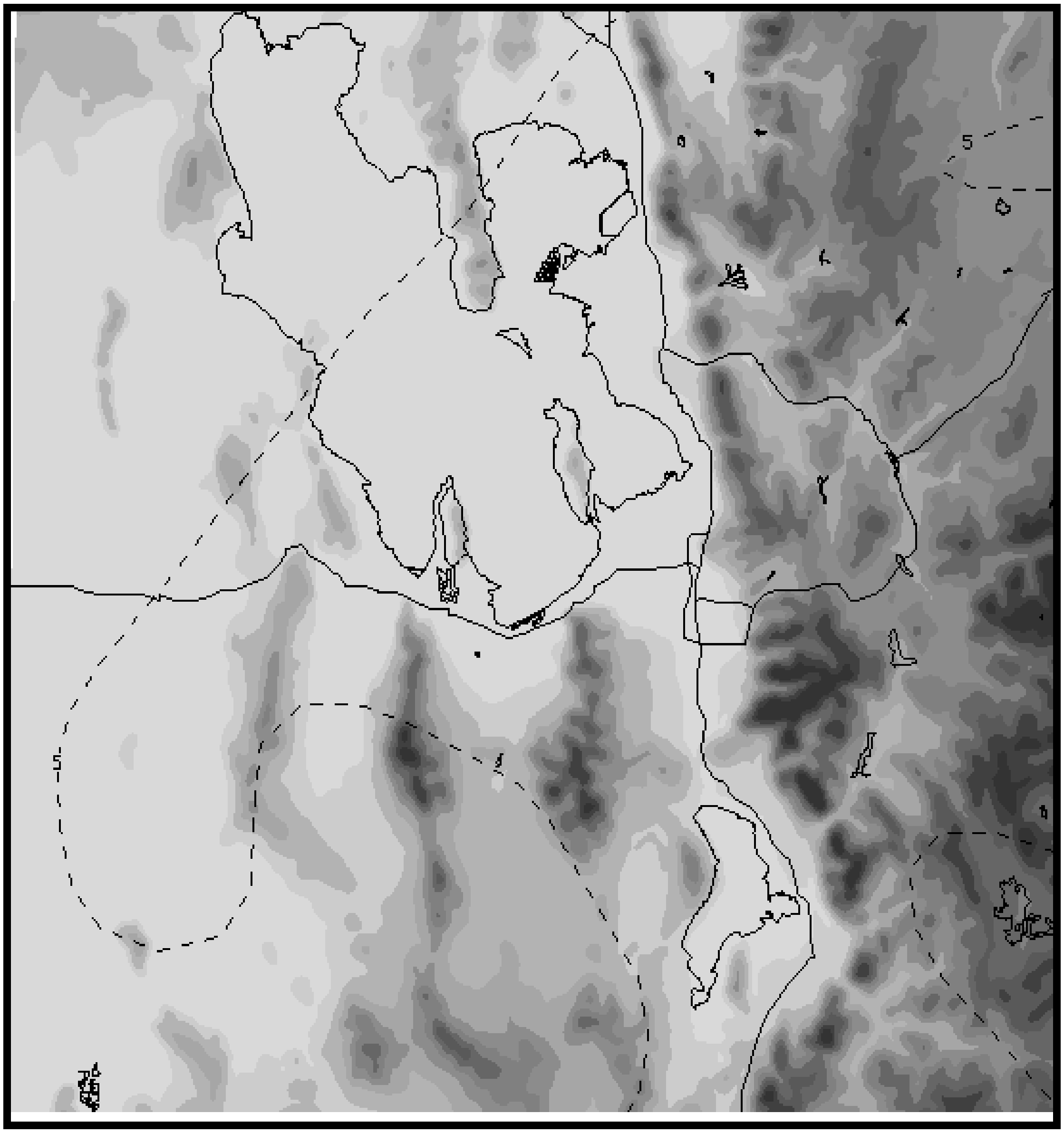
(a)

Figure 5.4. Spatial map of the precipitation forecast for IOP 4 from the a) Eta and b) MM5. Contours are isohyets incremented every 5 mm.



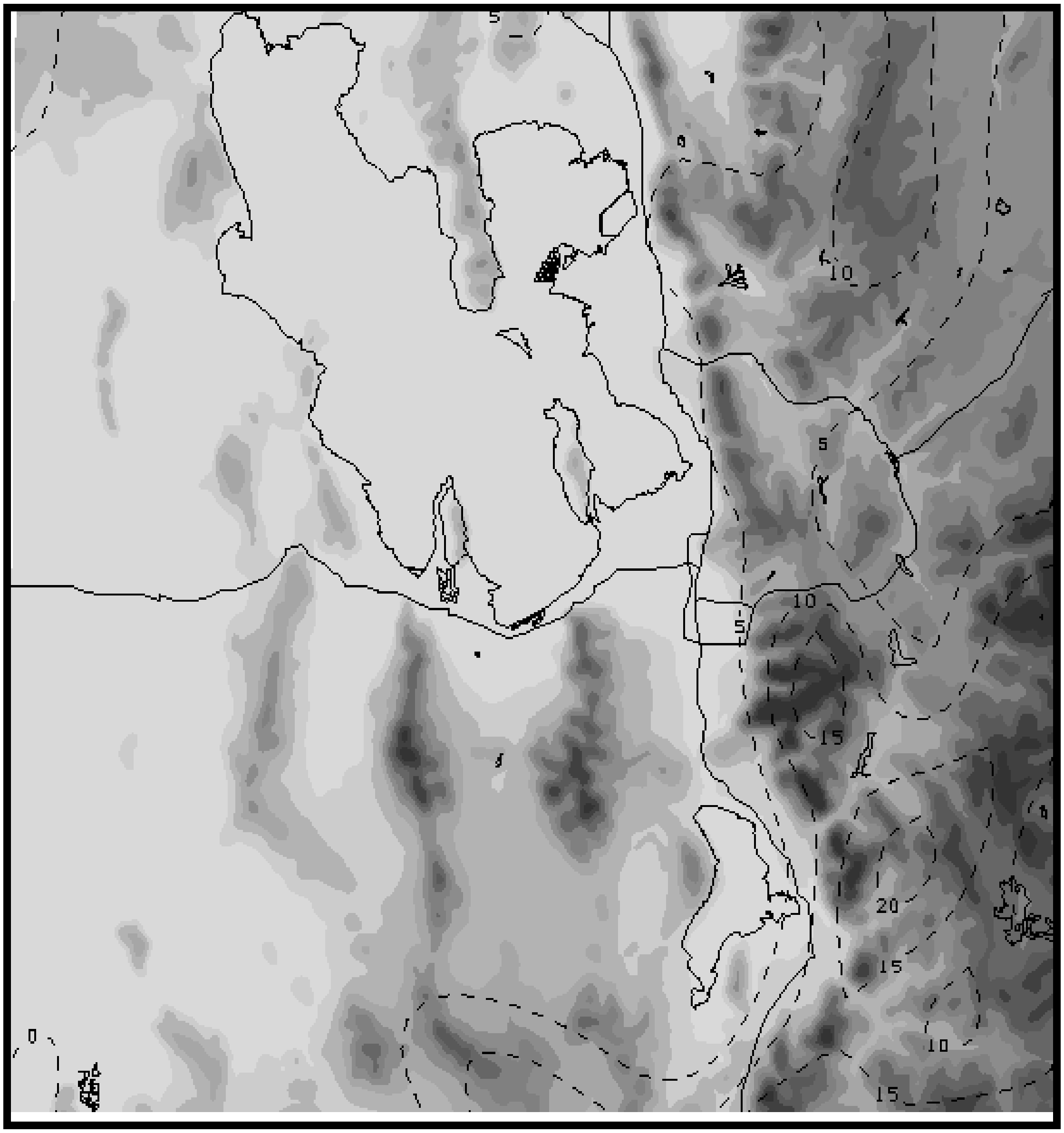
(b)

Figure 5.4. (Continued)



(a)

Figure 5.5. Spatial map of the precipitation forecast for IOP 5 from the a) Eta and b) MM5. Contours are isohyets incremented every 5 mm.



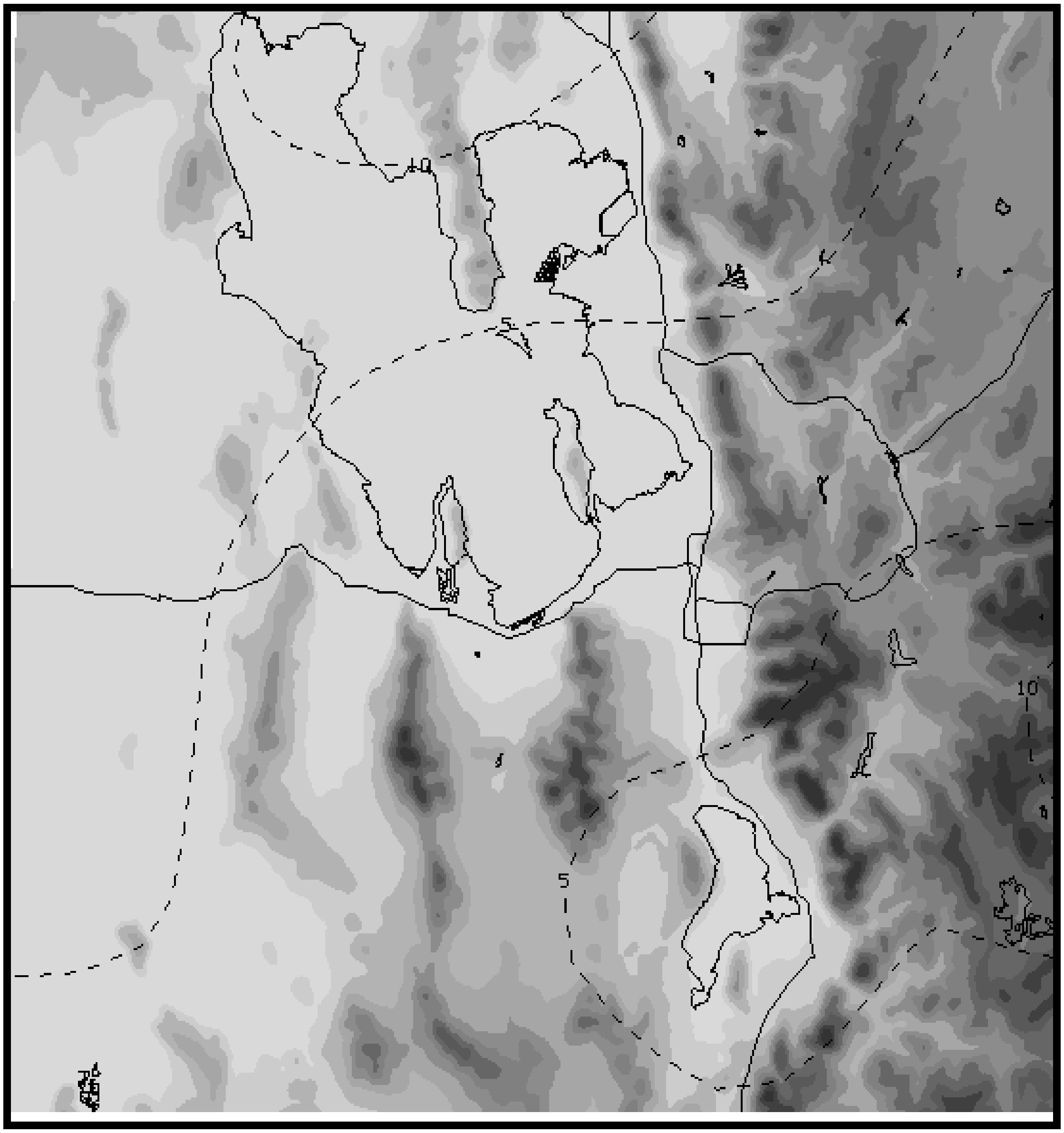
(b)

Figure 5.5. (Continued)

were less than 10 mm throughout the region, which is consistent with that observed at some stations but less than observed at other stations (Fig. 4.14). The model forecast missed the enhanced precipitation observed in the Tooele Valley.

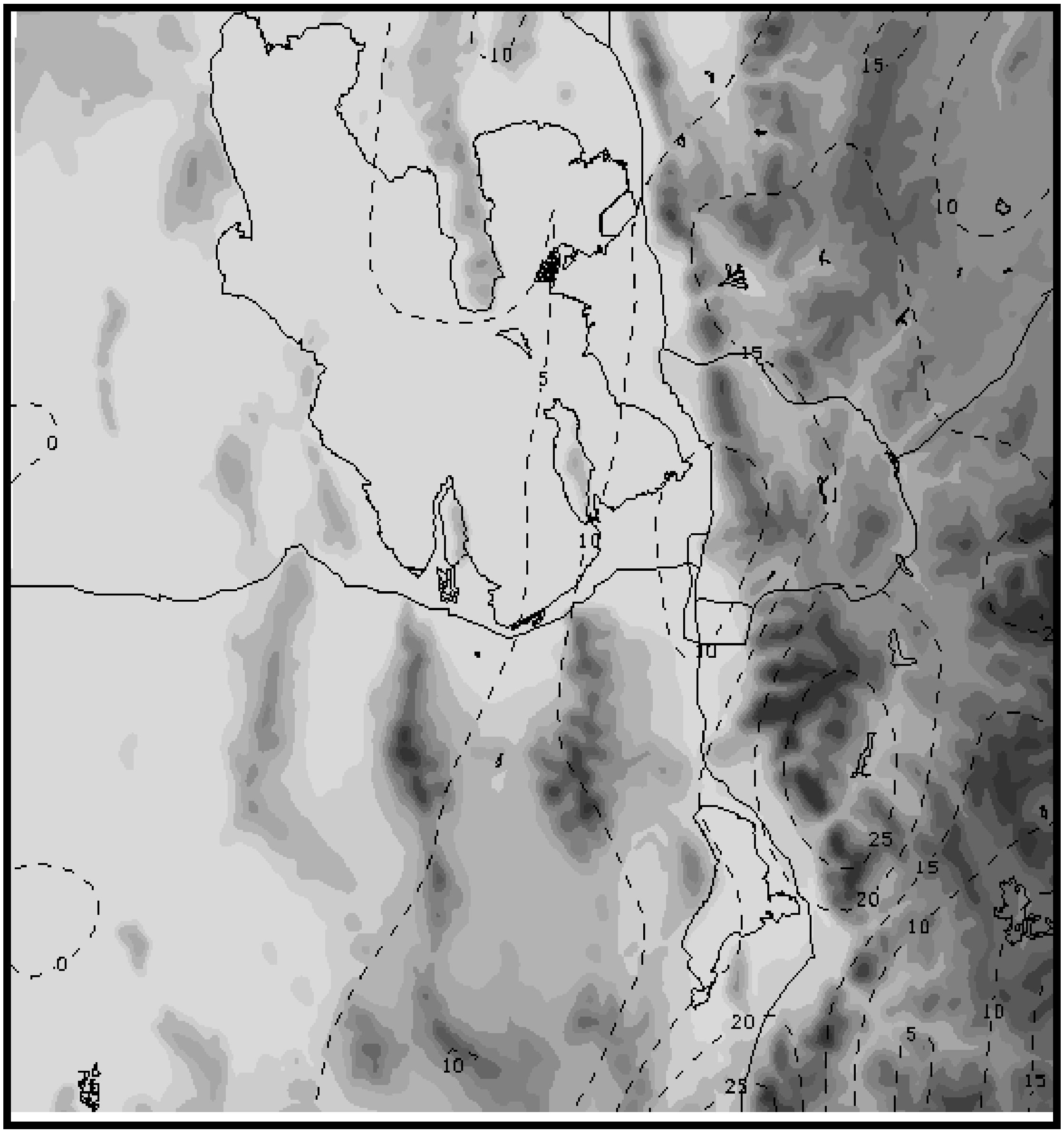
The MM5 forecast is shown in Fig. 5.5b. This model predicted weak orographic enhancement along the Wasatch, with maxima in the mountains southeast of Salt Lake City and east of Provo. The locations of the model's precipitation maxima are inconsistent with that observed. The model predicted a maximum of greater than 15 mm to occur over the Cottonwoods area, but most of the observed values there are less than 10 mm. As with the Eta, the MM5 also missed the Tooele Valley event. The model predicted less than 5 mm for all locations west of the Wasatch with the exception of a small area south of the Tooele Valley. Because the spatial forecasts of both the Eta and MM5 had significant errors, it appears that the mesoscale evolution of the precipitation band was not properly predicted by the models during this IOP.

The model forecasts for the convective event of IOP 6 are depicted in Fig. 5.6. As was shown in Fig. 4.18, slight enhancement was observed immediately upstream and along the crest of the Wasatch and Oquirrhs. The Eta forecast (Fig. 5.6a) shows a broad region of minimum values along a northeast-southwest oriented band, with two small maxima located north of the Great Salt Lake and over the high model terrain along the eastern edge of the region. This structure is not evident in the observations and as a result, precipitation was underforecast over most of the region but overforecast north of the Great Salt Lake. In fact, most of the highest observed totals lie within the area that was forecast to have minimum values.



(a)

Figure 5.6. Spatial map of the precipitation forecast for IOP 6 from the a) Eta and b) MM5. Contours are isohyets incremented every 5 mm.



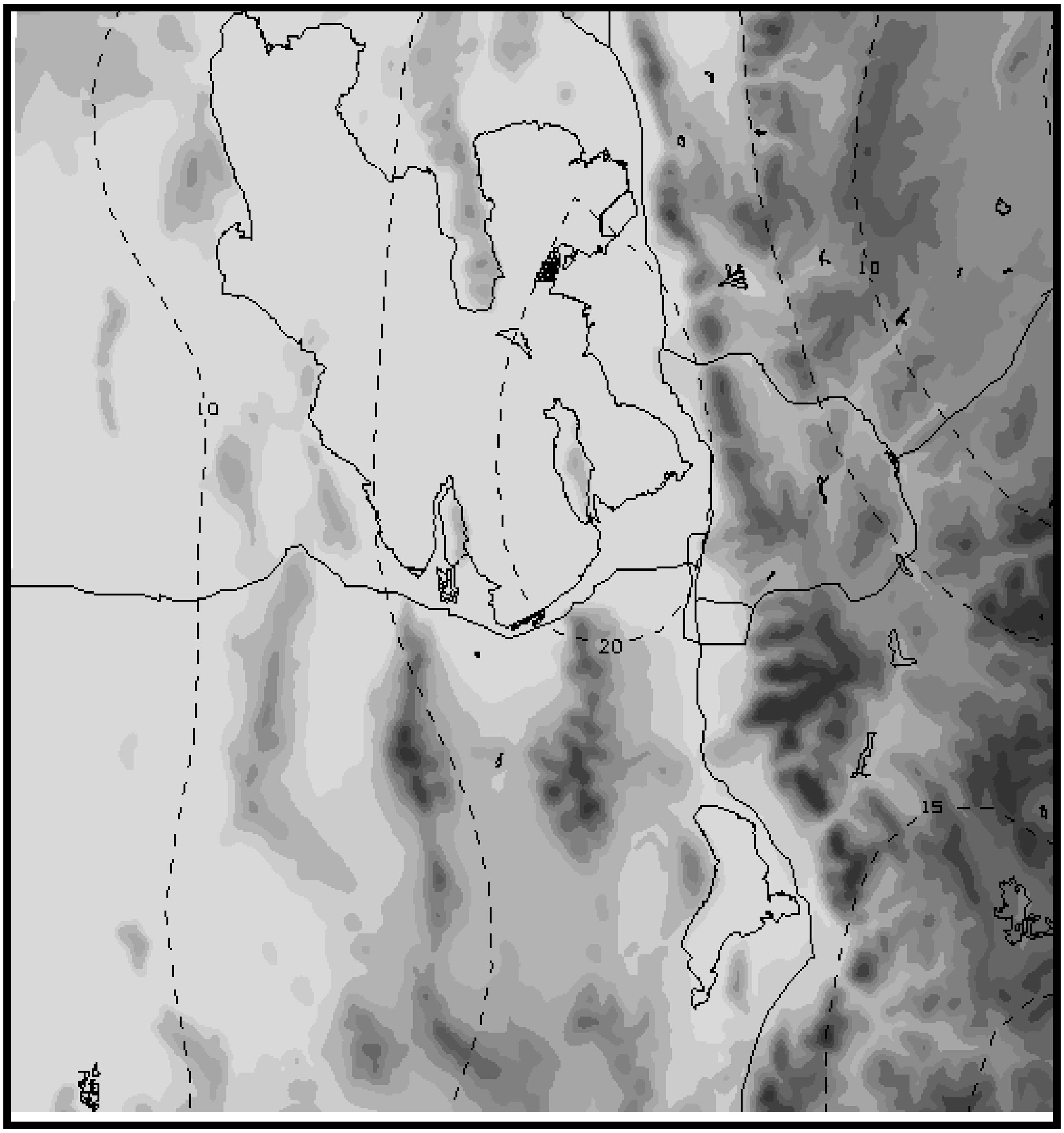
(b)

Figure 5.6. (Continued)

The MM5 forecast (Fig. 5.6b) captures the enhancement of precipitation along the Wasatch crest better than the Eta. The MM5 placed a maximum with values greater than 25 mm in the mountains northeast of Provo. This maximum overpredicted most of the observed values along that area of the Wasatch crest by about 5 mm and was placed slightly too far to the south. A local minimum of less than 10 mm was forecast for the Wasatch Front and Wasatch Range near Salt Lake City. This minimum is inconsistent with the observations, which show precipitation values greater than 15 mm in that area. The model appears to have forecast the greatest enhancement of precipitation on the southern slopes of the highest model terrain. This would be consistent for predominantly southerly flow, which was the case during this IOP.

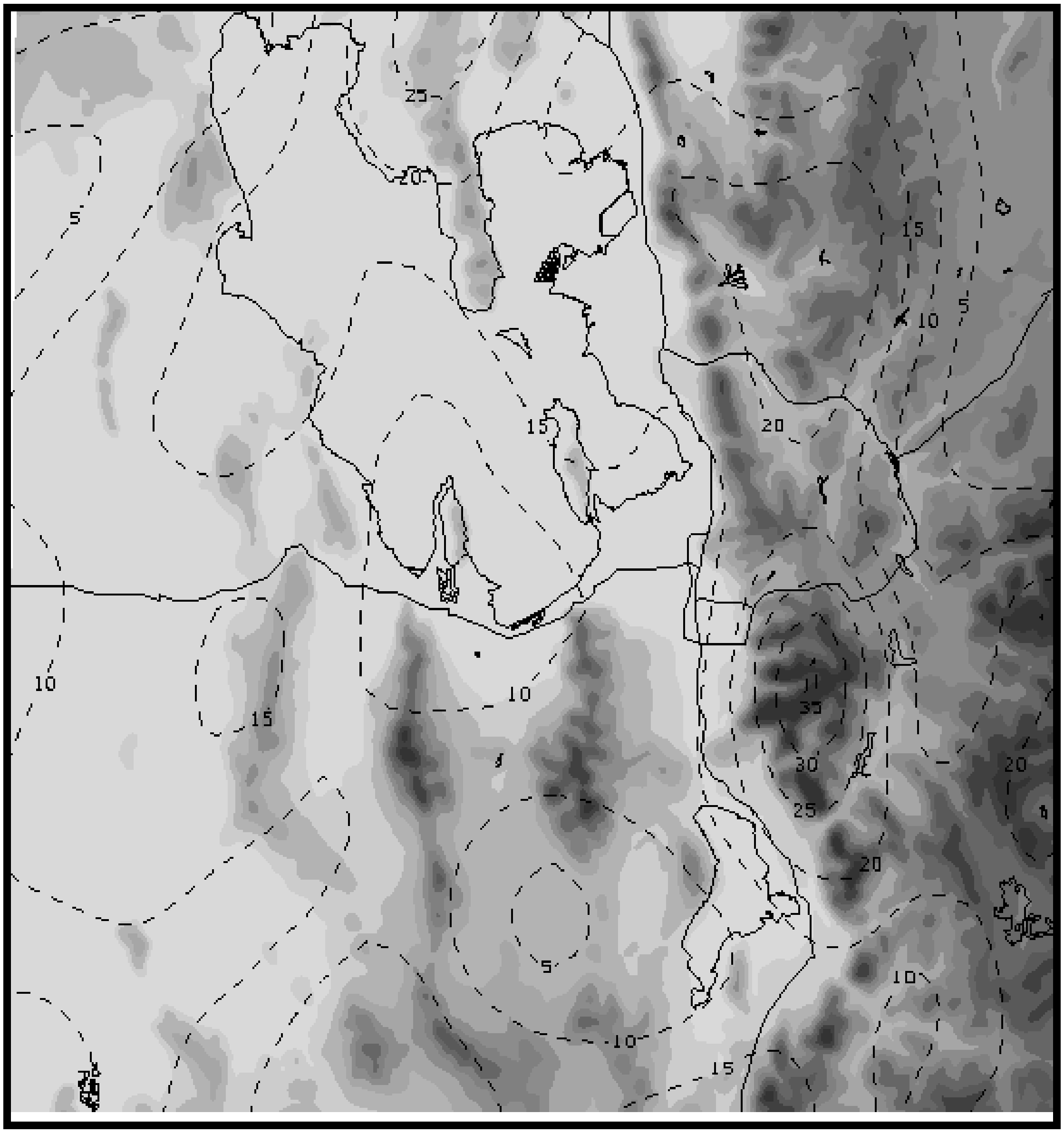
The forecasts for IOP 7 are shown in Fig. 5.7. This was a complex event with strong orographic enhancement, and precipitation was also observed over the Great Salt Lake (Fig. 4.21). The Eta forecast (Fig. 5.7a) shows a maximum of greater than 20 mm near the center of the region, right over the southeastern portion of the Great Salt Lake. This maximum is not evident in the observations. However, this placement may have been due to the model forecasting enhanced precipitation upstream of the mountains, since its location corresponds to the base of the Wasatch in the model terrain. The Eta's QPF values range from 10-20 mm throughout most of the region. The values correspond well with a majority of the observations with the exception of those at high elevations. As with the Eta's forecasts for the previous IOPs, a detailed structure of the observed precipitation distribution is lacking.

The MM5 forecast is shown in Fig. 5.7b. This model accurately placed the maximum in the Cottonwoods area southeast of Salt Lake City. The forecast maximum



(a)

Figure 5.7. Spatial map of the precipitation forecast for IOP 7 from the a) Eta and b) MM5. Contours are isohyets incremented every 5 mm.



(b)

Figure 5.7. (Continued)

was around 35 mm, which agrees with many of the observations in that area. Another area of greater than 20 mm was forecast to occur in the mountains east of Ogden. Values of that magnitude were observed in that general vicinity, but the size of the forecast maximum is too large and the area was shifted to the east of the Wasatch crest. No enhancement was forecast for the Oquirrhs. However, the model did produce enhanced precipitation over the Cedar Mountains west of the Stansburys. This may be due in part to the Cedars, Stansburys, and Oquirrhs not being resolved as separate ranges by the model. Therefore, enhancement was predicted only on the western slopes of the single, broad model mountain range. It is interesting to note that the model did correctly forecast the relatively large total observed in the west desert. The northern part of the region was also forecast to have totals greater than 20 mm, which is consistent with the 22 mm observed at the Thiokol site.

The spatial maps above show that the MM5 forecasts had the most spatial detail, as is expected with its higher resolution. However, in terms of quantitative totals, the Eta model can perform just as well or even better than the MM5 in some cases, although its forecasts lack fine-scale variability. It also appears that the precipitation distribution is highly dependent on the model terrain. For example, the MM5 showed detailed structure in terms of orographic effects, but enhanced areas were placed with respect to the model terrain rather than the actual terrain. Therefore, the detail of the MM5 forecasts may be of negative value if the placement of some of the maxima and minima are significantly different than observed. Finally, model skill varies greatly by event, with precipitation during some IOPs forecast better than others.

Zone Forecasts

The subjective evaluation of QPF skill such as that done in the previous section is difficult to quantify. One benefit of the enhanced monitoring during IPEX is that model forecasts made every day can be verified against the observed precipitation during each corresponding period. However, the variability in observed precipitation within the IPEX domain and the mismatch between the observed and model terrain make it difficult to contrast the observed and simulated precipitation.

As a novel approach to quantify the QPF skill, the observed precipitation in different forecast zones is compared to that forecast by the models. Surface stations and model grid points are grouped into one of seven zones that correspond to the climatological zones used by the SLC NWSFO to issue forecasts. Since the AVN and Eta output grids are relatively coarse, few grid points are located in each zone. Therefore, this method is applied only to the MM5 forecasts.

The seven climatological zones that are used in this study are: Great Salt Lake Desert and Mountains, Salt Lake and Tooele Valleys, Northern Wasatch Front, Southern Wasatch Front, Northern Wasatch Mountains, Southern Wasatch Mountains, and Wasatch Mountain Valleys (Fig. 5.8). Table 5.1 shows the number of available observations and model grid points in each zone. Note that the actual number of observations can be lower on any given day due to outages.

For each zone, the areal mean and standard deviation for each 24-h period ending at 0000 UTC were computed from the values at both the model grid points and the surface stations. Only the 1200 UTC model run was used, so the verification period corresponds to

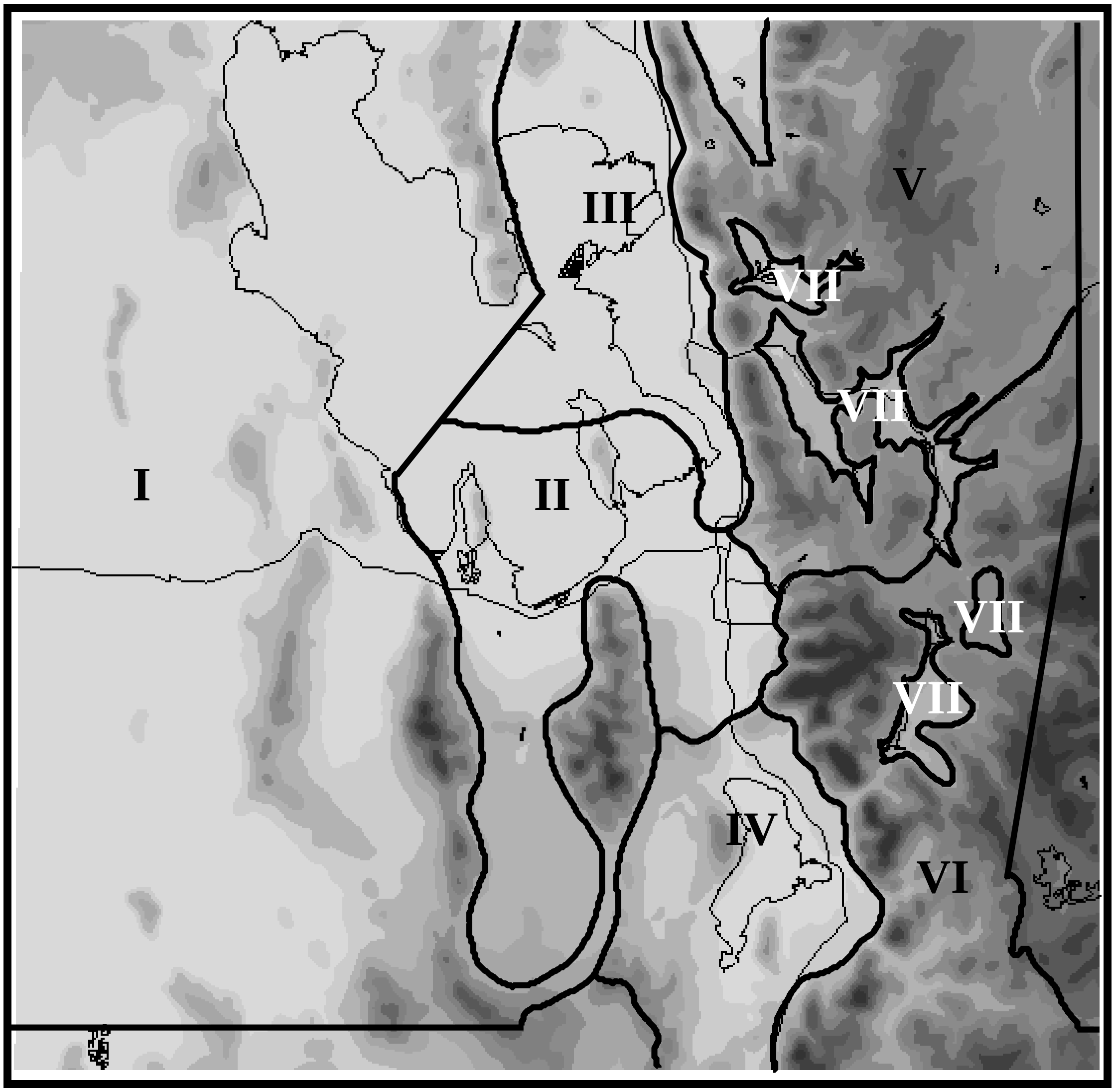


Figure 5.8. Boundaries for the forecast zones being evaluated: I) Great Salt Lake Desert and Mountains, II) Salt Lake and Tooele Valleys, III) Northern Wasatch Front, IV) Southern Wasatch Front, V) Northern Wasatch Mountains, VI) Southern Wasatch Mountains, VII) Wasatch Mountain Valleys.

Table 5.1. Number of observational stations and MM5 model grid points available in each forecast zone.

Forecast Zone	# of Obs Stations	# of Grid Points
Great Salt Lake Desert and Mountains	8	130
Salt Lake and Tooele Valleys	14	29
Northern Wasatch Front	6	22
Southern Wasatch Front	13	17
Northern Wasatch Mountains	13	38
Southern Wasatch Mountains	18	36
Wasatch Mountain Valleys	14	8

the 12-36-h forecast period. The period begins 4 February due to missing MM5 runs at the beginning of the month.

This approach focuses upon the following: how well does the MM5 predict the mean precipitation in a climatological zone compared to that observed? Using this approach, there is no interpolation of the precipitation on the model grid to the gauge locations. Rather the degree to which the forecast and observed means agree is judged based upon the observed and predicted variability within the zone. In other words, if the forecast mean is more than 1 standard deviation above (below) the observed mean, then it becomes obvious to conclude that the model has overforecast (underforecast) precipitation in that zone. The Student's t test of the difference of two means can be used to quantify the likelihood that the sample of precipitation forecasts in a zone are from the same population as the sample of observed amounts (Panofsky and Brier 1968). Hence, satisfying the null hypothesis is equivalent to a skillful forecast. Finally, it should be recognized that this approach penalizes a model that does not accurately specify the actual terrain. For example, the western slopes of the MM5's Wasatch Mountains penetrate into the valley zones.

This approach is not without limitations. The spatial distribution of available gauges in each zone is not uniform. For example, there are more gauges in the Cottonwood Canyons/Park City area than in other parts of the Southern Wasatch Mountains zone. Hence, the observed standard deviation available here may underestimate the actual variability of precipitation in each zone, which could lead to an overestimate of the model skill.

Figure 5.9 shows the areal means and standard deviations of the observed precipitation and MM5 forecasts for the Great Salt Lake Desert and Mountains. Since the number of gauges is so much smaller than the number of model grid points in this zone, the results should be viewed with caution. In general, precipitation in this zone was underpredicted by the model during the IPEX period. While the model performed very well during the 24-h period ending at 0000 UTC 12 February for both the mean and variability of precipitation in the zone, especially large errors are evident during the periods ending 0000 UTC 13 and 25 February. These days are associated with the strong orographic events of IOP 3 and IOP 7, and as shown in the previous section, the model had difficulty forecasting orographic enhancement of precipitation over the Oquirrhs and Stansburys during those IOPs. One important point to note is that of the eight observations in this zone, three are located in the Oquirrh and Stansbury mountains, so the observed mean may not be representative of the entire zone.

The results for the Salt Lake and Tooele Valleys are shown in Fig. 5.10. The precipitation forecast skill is more variable in this zone than in the previous one. The mean precipitation was overforecast as many times as it was underforecast. It also appears that the model performed very well on some occasions, such as during the periods ending 0000 UTC 12, 14, 17, 22, and 23 February, while at other times, it performed poorly (the periods ending 0000 UTC 15, 16, 18, 19, and 21 February). The large errors for the periods ending at 0000 UTC 18 and 19 February are mostly the result of the forecast bust of the localized Tooele Valley snowstorm during IOP 5, as shown in the previous section.

In the Northern Wasatch Front (Fig. 5.11), the model had a tendency to overforecast precipitation. The small sample of gauges available in this zone should be

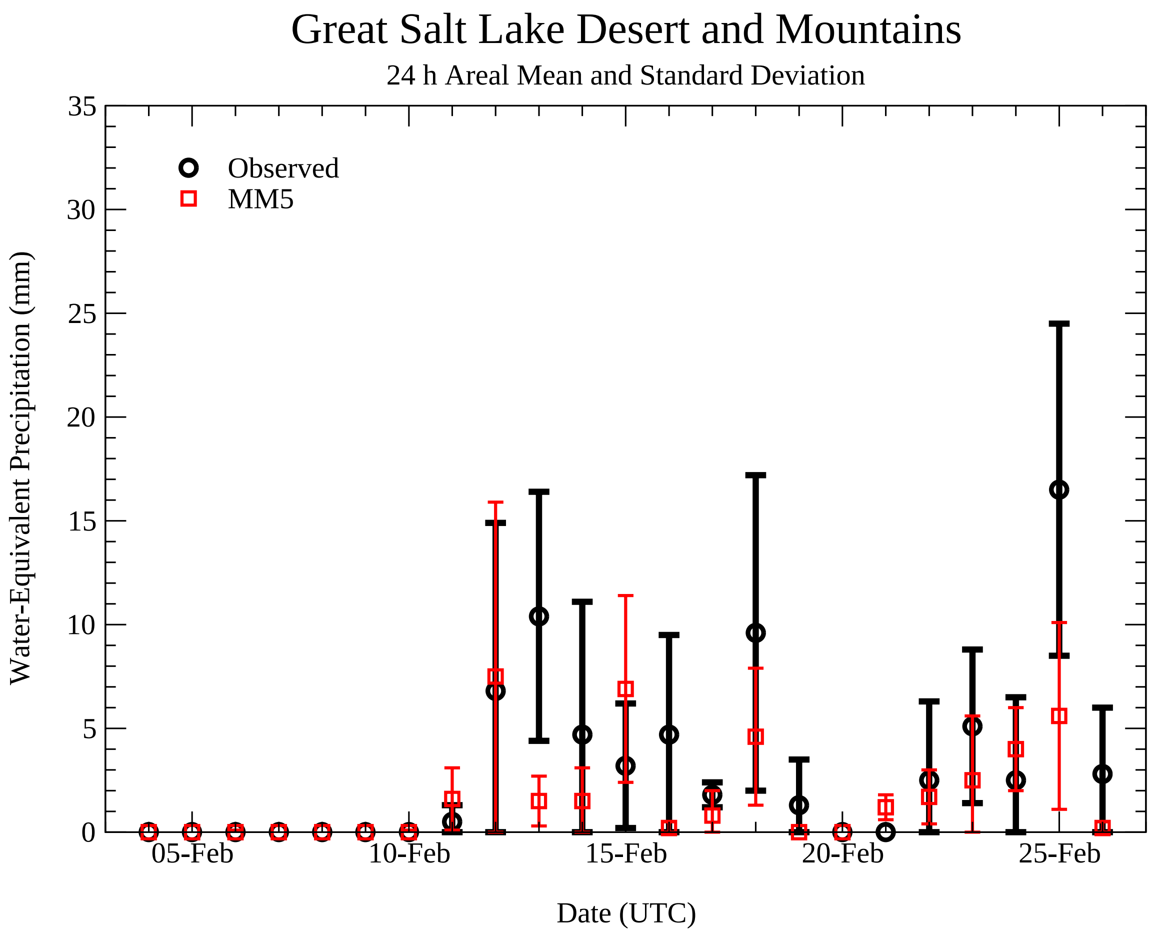


Figure 5.9. Observed and MM5 24-h areal mean and standard deviation for the forecast zone Great Salt Lake Desert and Mountains. Dates denote the 0000 UTC end time of each 24-h validation period, e.g., the values plotted at 25 February denote the observed precipitation valid from 0000 UTC 24 February-0000 UTC 25 February and the 12-36-h forecast initialized at 1200 UTC 23 February.

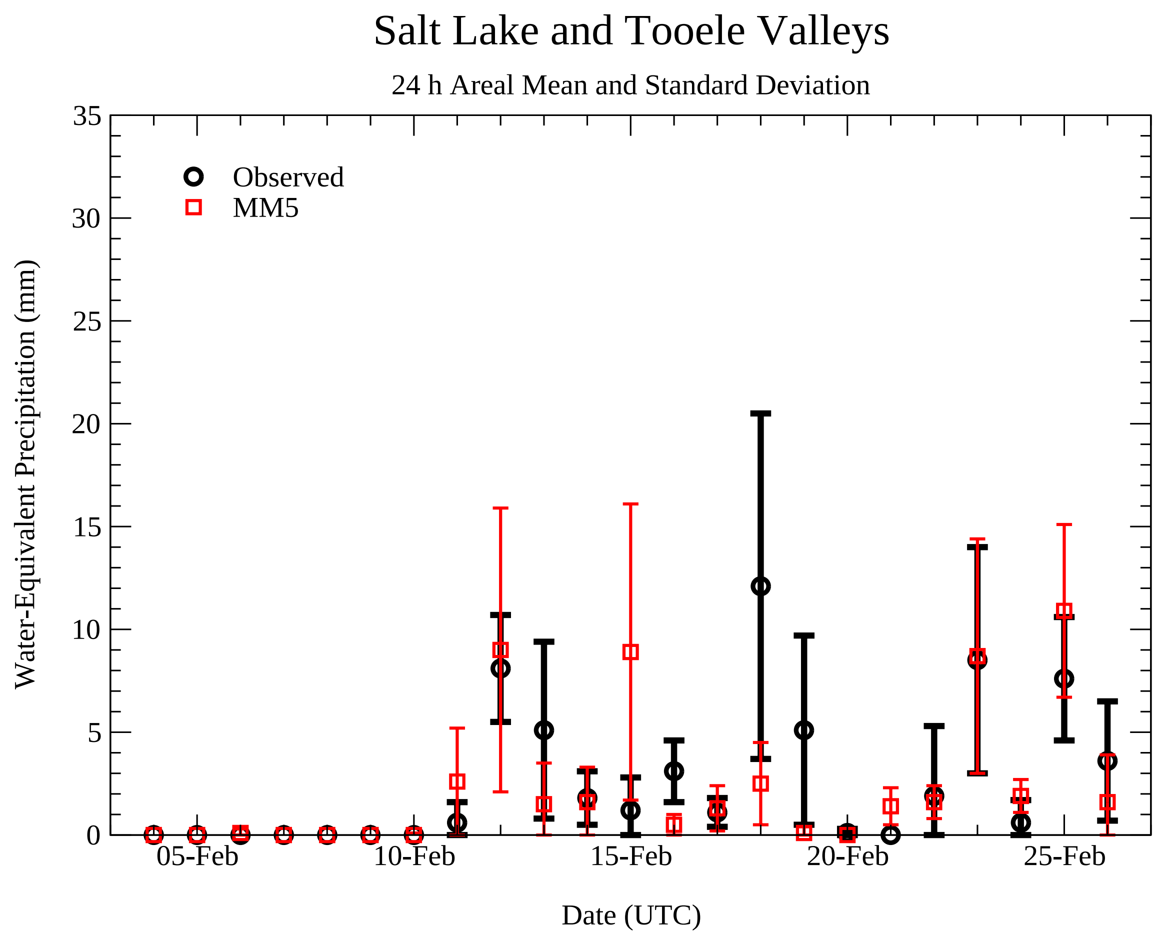


Figure 5.10. Observed and MM5 24-h areal mean and standard deviation for the forecast zone Salt Lake and Tooele Valleys. Dates denote the 0000 UTC end time of each 24-h validation period.

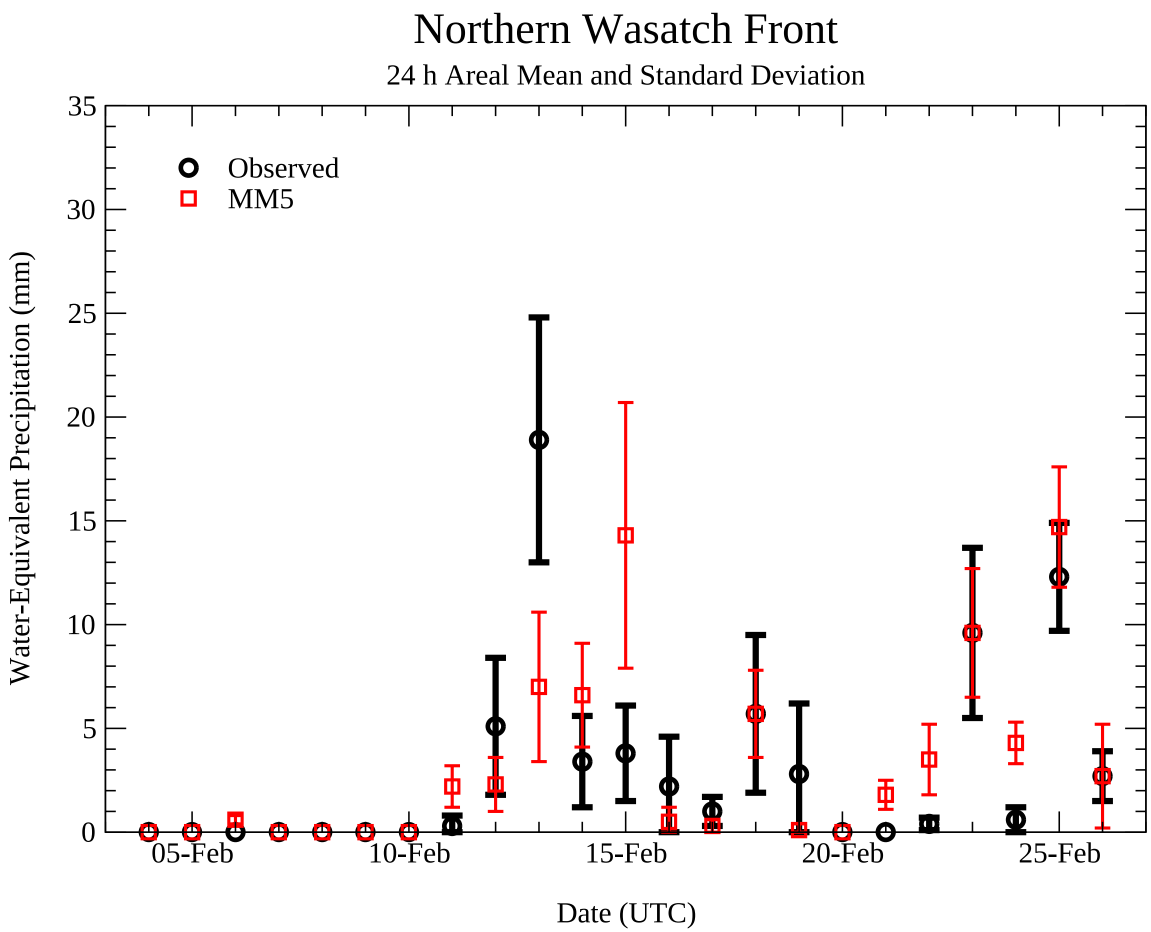


Figure 5.11. Observed and MM5 24-h areal mean and standard deviation for the forecast zone Northern Wasatch Front. Dates denote the 0000 UTC end time of each 24-h validation period.

considered, however. The model appears to be quite skillful on certain days, such as the periods ending 0000 UTC 18, 23, and 26 February, but there also days (the periods ending 0000 UTC 11, 13, 15, 21, 22, 24 February) when the errors were especially large.

As in the Salt Lake and Tooele Valleys, precipitation was overforecast about as many times as it was underforecast in the Southern Wasatch Front (Fig. 5.12), but the extent of the errors appears to be larger for cases of overforecasting rather than underforecasting. Significant errors are evident during the periods ending 0000 UTC 12, 13, 23, and 25 February. During the 24-h period ending at 0000 UTC 25 February, the observed precipitation had minimum values around Utah Lake east of Provo (Fig. 4.21). The model was apparently unable to accurately resolve the steep gradient in precipitation between this area and the adjacent mountains, and as a result, precipitation was overforecast during IOP 7, as evident in Fig. 5.7b.

In the Northern Wasatch Mountains (Fig. 5.13), the model had a greater tendency to underforecast rather than overforecast. However, it is interesting to note that the model errors are relatively small compared to some of the valley zones. The model was quite skillful for the periods ending 0000 UTC 17, 18, 23, 24, and 25 February. The quantitative precipitation for this zone during the orographic event of 24 February appears to have been forecast rather well. The model also performed relatively well during IOP 5. For IOP 6, the model was skillful for the period ending 0000 UTC 23 February, but it appears to have begun precipitation too early, since the mean for 22 February was overforecast. The forecasts for the periods ending on 13 and 14 February have larger errors than many of the other days. These two dates correspond to the strong orographic event of IOP 3, which was underforecast, as shown in Fig. 5.3b.

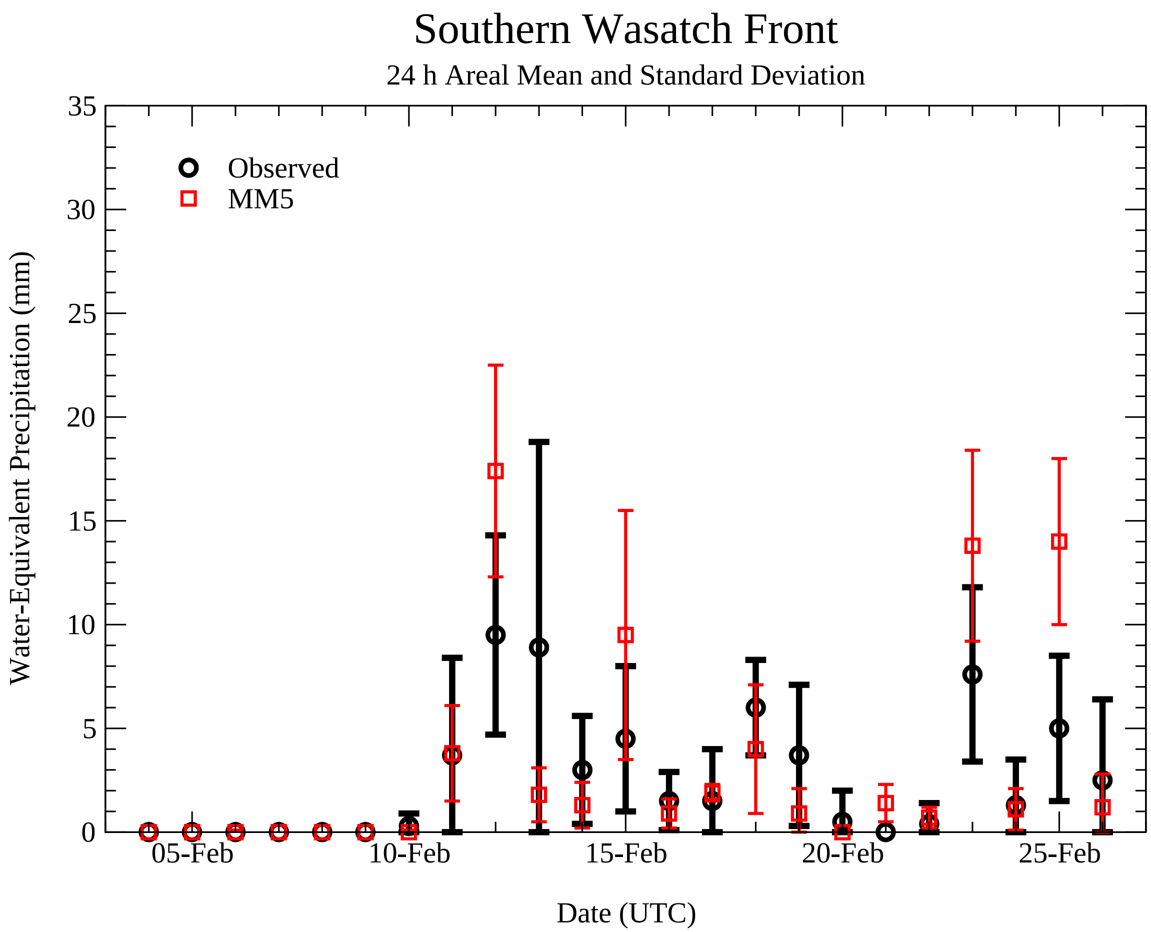


Figure 5.12. Observed and MM5 24-h areal mean and standard deviation for the forecast zone Southern Wasatch Front. Dates denote the 0000 UTC end time of each 24-h validation period.

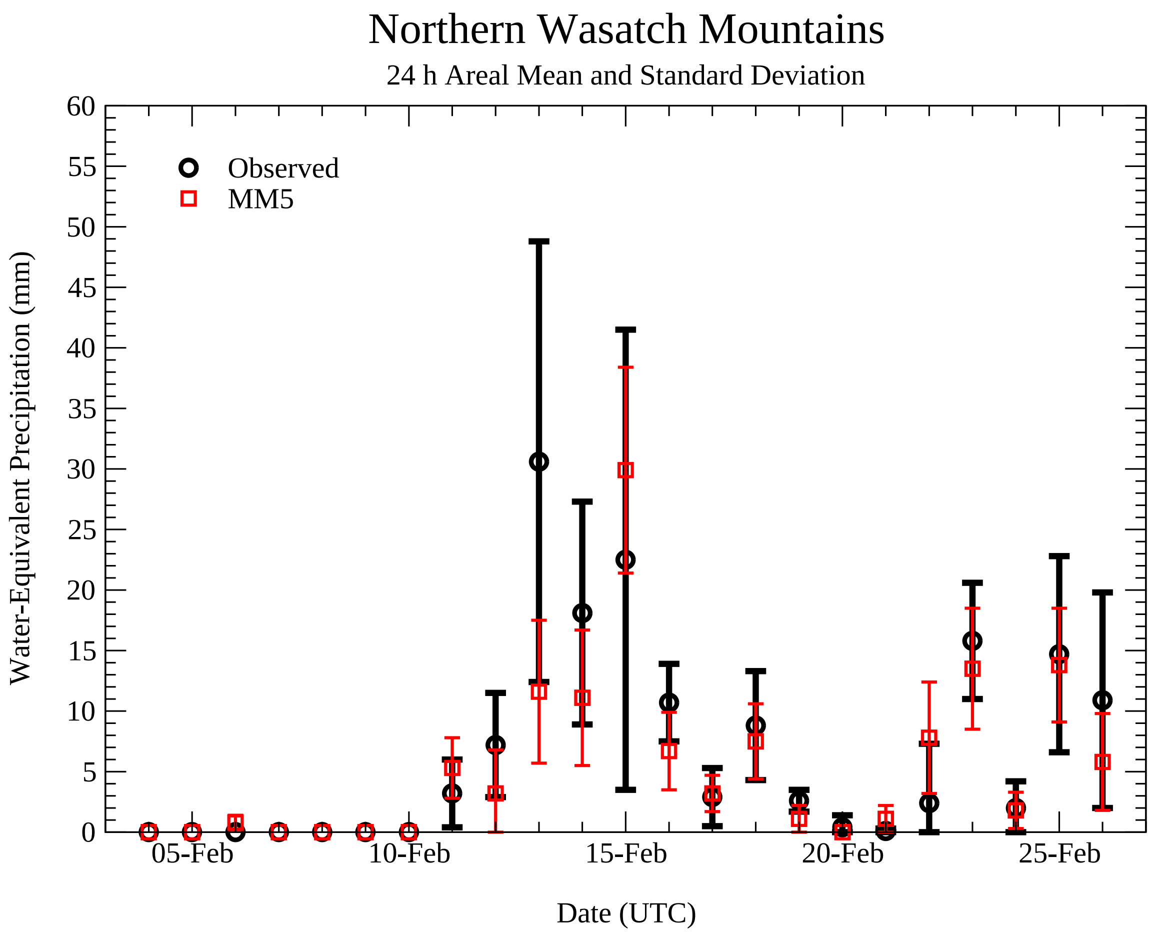


Figure 5.13. Observed and MM5 24-h areal mean and standard deviation for the forecast zone Northern Wasatch Front. Dates denote the 0000 UTC end time of each 24-h validation period.

The results for the Southern Wasatch Mountains are shown in Fig. 5.14. Unlike in the Northern Wasatch Mountains, the model had a tendency to overforecast in this zone. Greater orographic enhancement appears to have been forecast in this zone than in the Northern Wasatch Mountains. For example, the mean QPF for the period ending 0000 UTC 15 February is twice as large as the observed mean. In contrast, the mean QPF is lower, even though the observed mean is higher, in the north. Similarly, the errors during IOP 3 are not as large in this zone because the model predicted greater precipitation than in the north even though the observed values are lower. Examination of the mean values during IOP 7 also shows larger values forecast for the south.

The model trend in predicting orographic enhancement in the Wasatch is illustrated in the cumulative time series of observed and MM5 areal mean precipitation (Fig. 5.15). The MM5 favors more precipitation to occur in the southern Wasatch than in the northern Wasatch while the observed trends are more comparable for the available distribution of precipitation gauges.

The results for the Wasatch Mountain Valleys forecast zone are presented in Fig. 5.16. Because of their location on the lee side of the Wasatch crest, these valleys can be relatively dry compared to the mountain zones. However, because of the small size of these valleys with respect to the model's grid spacing, they are not resolved by the model, and few grid points lie within the climatological zone. Therefore, it is expected that the model would be unable to accurately forecast the rain shadowing that can occur in these valleys. This is evident in Fig. 5.16, as measurable precipitation on all but one day was overpredicted by the model. In most cases, the overprediction is extreme, with differences between the forecast and observed means greater than the standard deviation of the

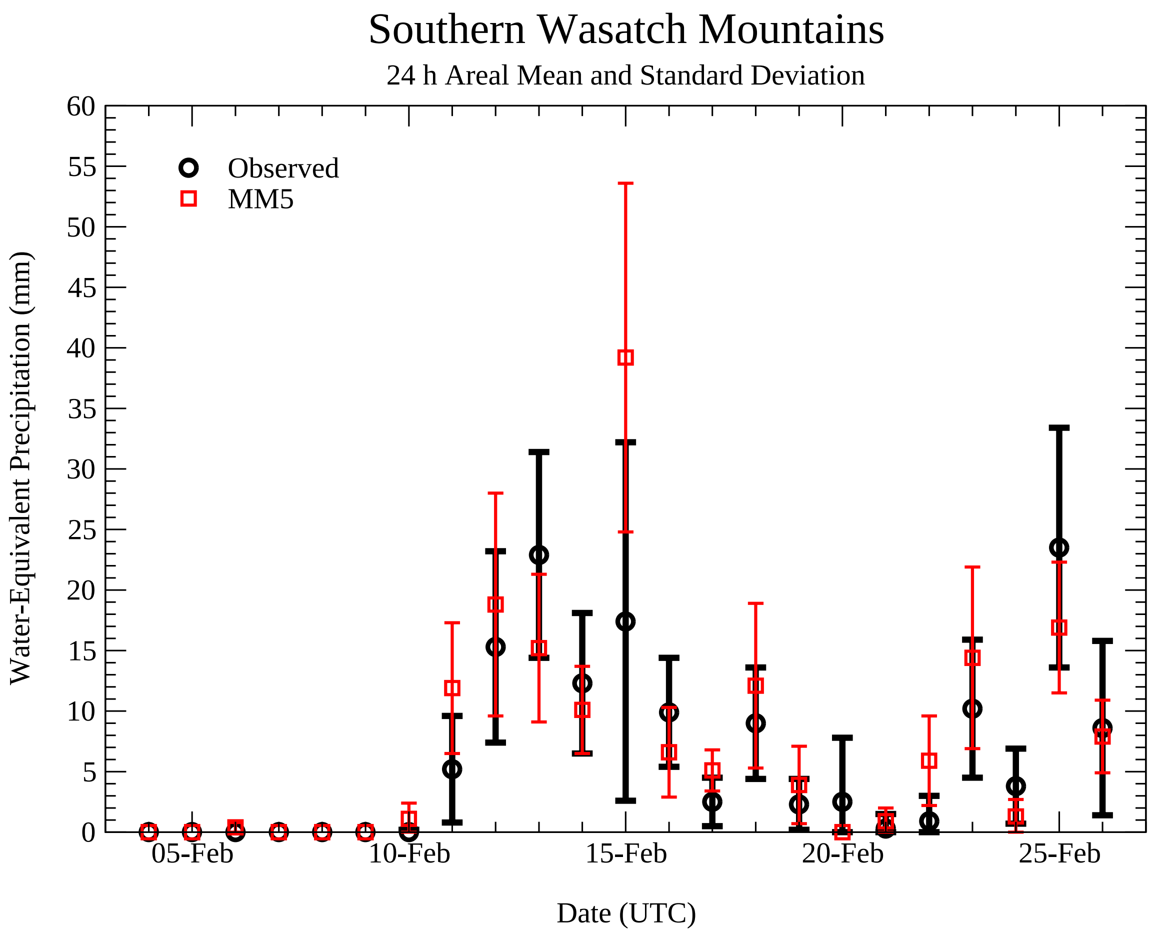


Figure 5.14. Observed and MM5 24-h areal mean and standard deviation for the forecast zone Southern Wasatch Mountains. Dates denote the 0000 UTC end time of each 24-h validation period.

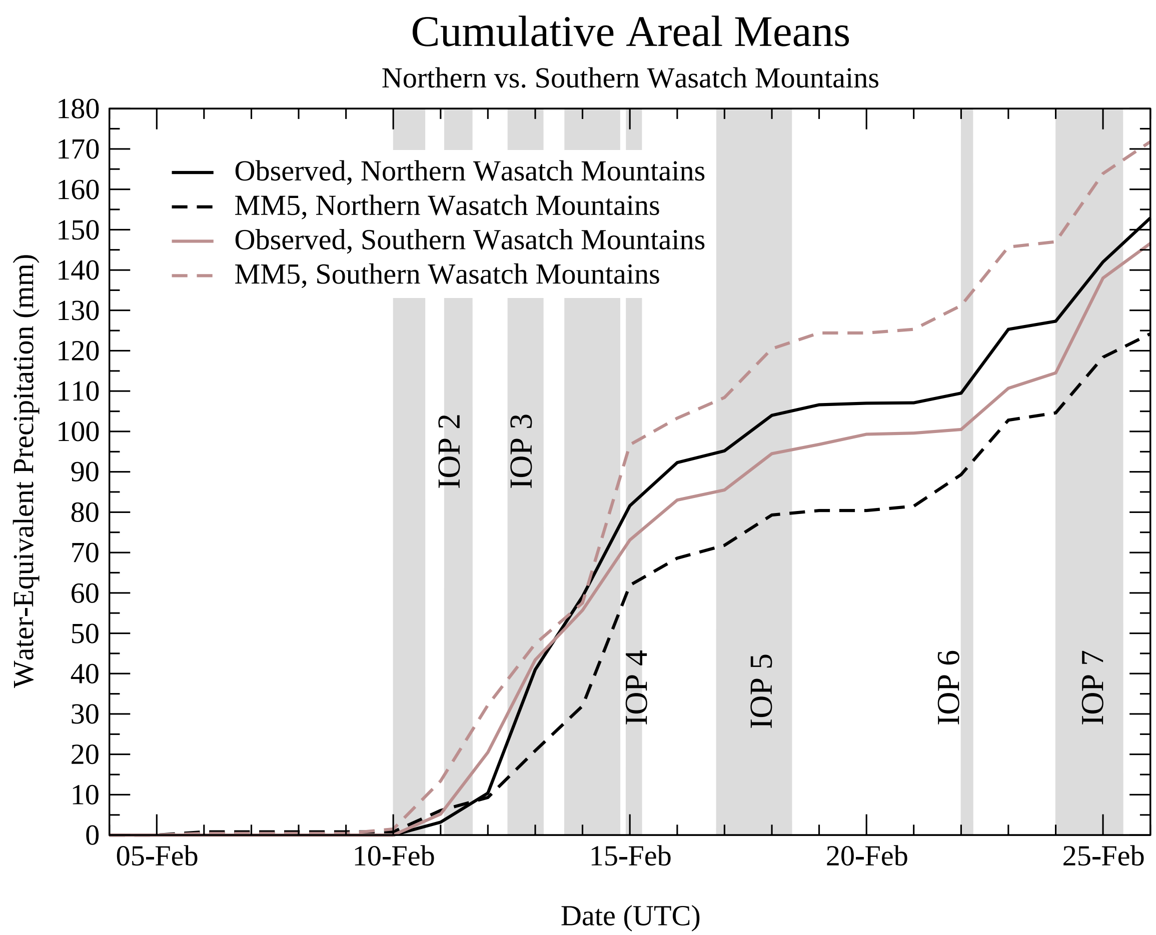


Figure 5.15. Cumulative observed and MM5 areal mean precipitation from the two forecast zones Northern Wasatch Mountains and Southern Wasatch Mountains. Shaded areas represent subjectively-determined periods of significant precipitation over the IPEX domain, with events corresponding to the IOPs labeled.

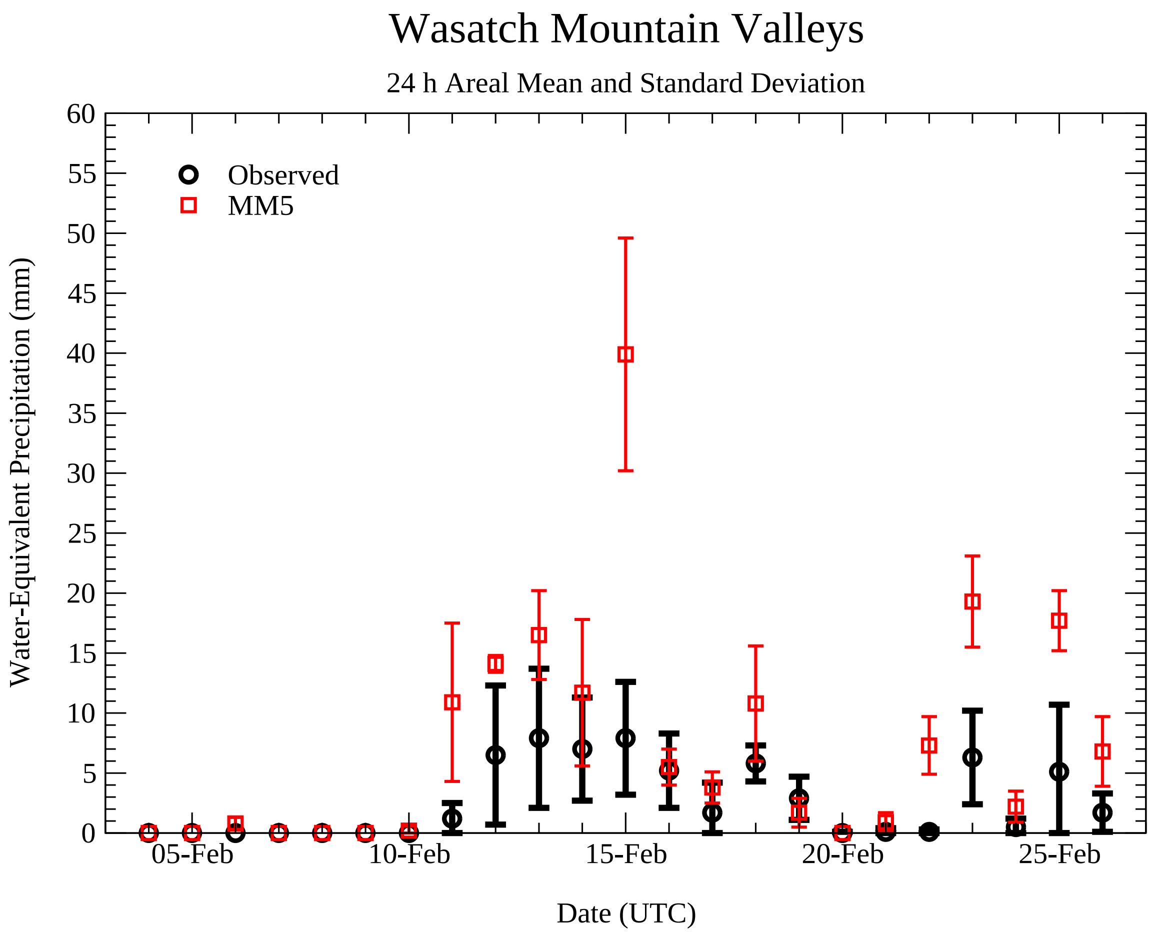


Figure 5.16. Observed and MM5 24-h areal mean and standard deviation for the forecast zone Wasatch Mountain Valleys. Dates denote the 0000 UTC end time of each 24-h validation period.

observed. Errors are especially large on days associated with significant orographic precipitation, such as the periods ending 0000 UTC 15 and 25 February. In contrast, the model performed better for the precipitation associated with the squall line during the period ending 16 February. As should be expected, the model's mean QPF values are more consistent with those in the mountain zones, whereas the observed means are more consistent with those in the valley zones.

The results from the individual zones are affected to some degree by the limited sample size of gauges. Therefore, a comparison between the observations and model forecasts are also made for two larger aggregate areas. One of these areas consists of the three zones located along the Wasatch Front: Salt Lake and Tooele Valleys, Northern Wasatch Front, and Southern Wasatch Front. The other area consists of the zones located in the Wasatch Mountains: Northern Wasatch Mountains, Southern Wasatch Mountains, and Wasatch Mountain Valleys.

The areal means and standard deviations for the combined Wasatch Front zones are shown in Fig. 5.17. Precipitation along the Wasatch Front was generally overpredicted. This agrees with the results from the individual zones, since the overforecasting errors are large in the Northern Wasatch Front and Southern Wasatch Front, even though errors in the Salt Lake and Tooele Valleys are due equally to over- and underforecasting. Overforecasting in the combined Wasatch Front zones is likely a result of the region's proximity to the mountains. As shown in Fig. 3.3, the mountains in the model begin further west than observed, and the Tooele Valley is not well resolved. Therefore, the forecast values tend to be larger due to the higher model terrain compared to that observed.

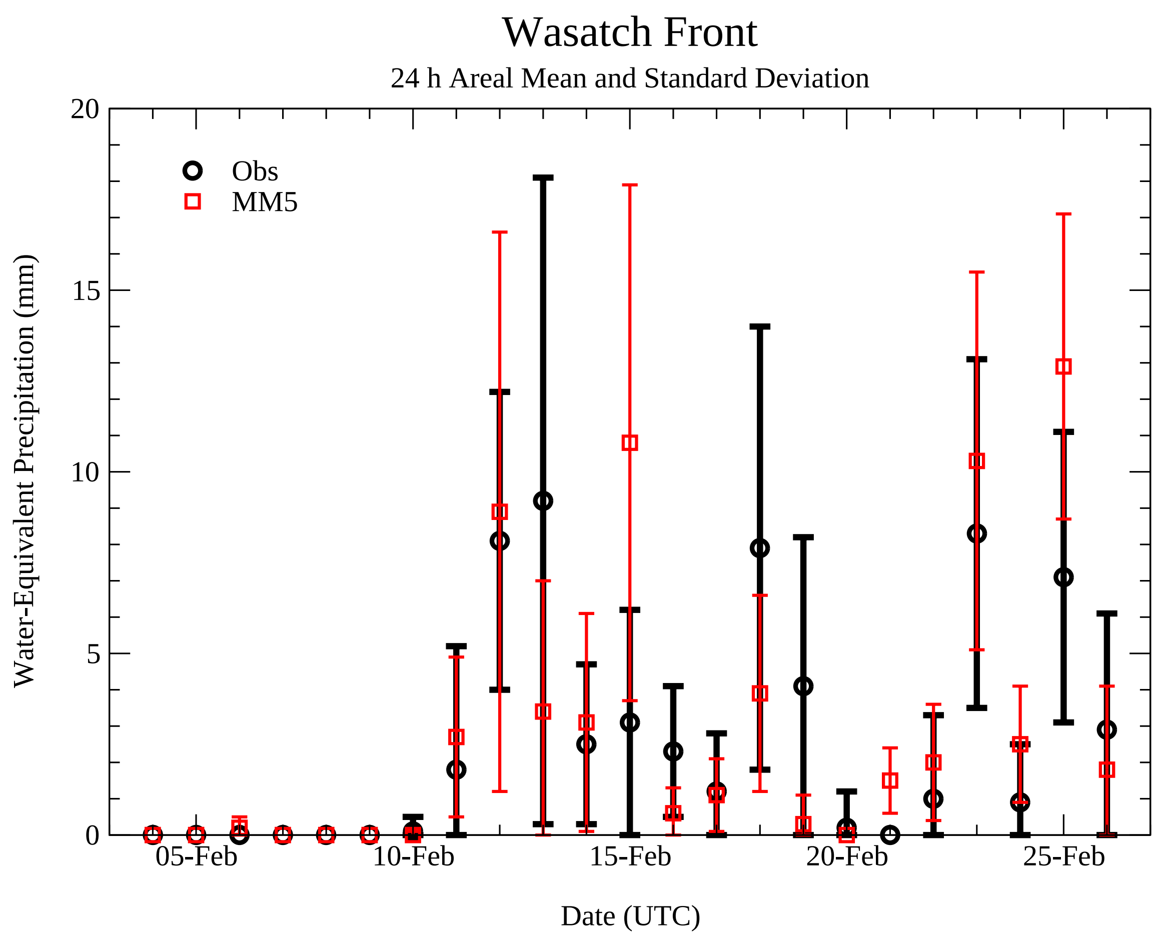


Figure 5.17. Observed and MM5 24-h areal mean and standard deviation for the combined Wasatch Front zones. Dates denote the 0000 UTC end time of each 24-h validation period.

For the mountain region (Fig. 5.18), overforecasting occurred slightly more frequently than underforecasting, and the errors appear to be larger for cases of overforecasting than for underforecasting. The underforecasting trend evident in the Northern Wasatch Mountains is compensated for by including the Southern Wasatch Mountains, where overforecasting was more prevalent, and the Wasatch Mountain Valleys, where precipitation was significantly overpredicted. The forecast means correspond well with the observed means on many occasions, although several days with large errors are also evident, including the periods ending at 0000 UTC 15 February, in which the orographic precipitation was overpredicted, and the period ending 22 February, in which the model appeared to begin precipitation too early for the IOP 6 event.

The interpretation of model error from the preceding figures is subjective and focuses upon evaluating the deviation of the predicted mean from the observed mean relative to the observed variability in precipitation. In order to provide an objective measure of over- and underforecasting, the null hypothesis is made that the observed and predicted means are from the same population. Student's t values were calculated for each zone, as well as the two combined zones, after normalizing the precipitation distribution by square-root transformation (Panofsky and Brier 1968). If the Student's t value for the difference of these means is outside of the ± 3 range, then the null hypothesis may be rejected at the 1% level for sample sizes of 13 or greater. Student's t values greater than 3 indicate an overforecast, whereas values less than -3 indicate an underforecast.

The Student's t values for each individual zone as well as the combined Wasatch Front and Wasatch Mountains zones are shown in Fig. 5.19. To a large degree, the results simply confirm the points made earlier. The largest errors occur in the Great Salt Lake

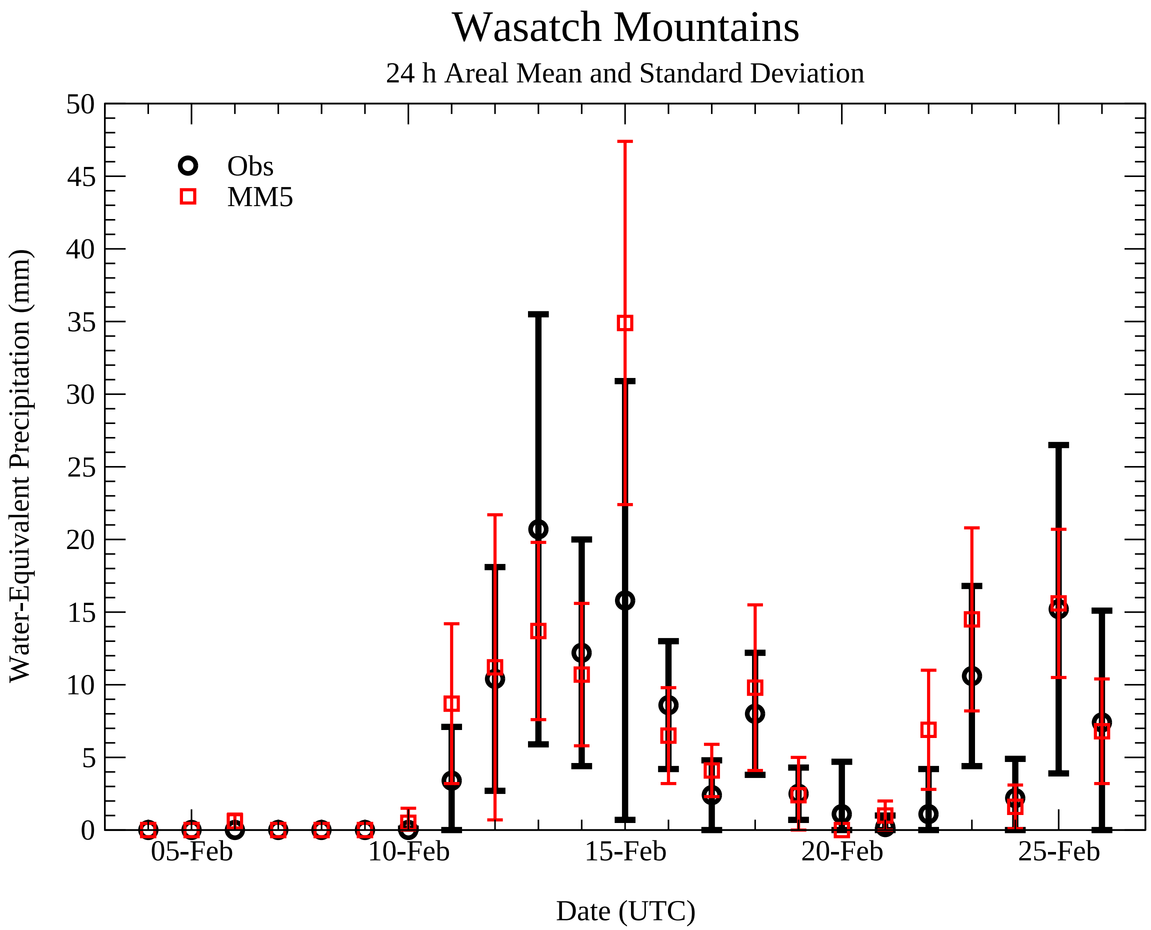
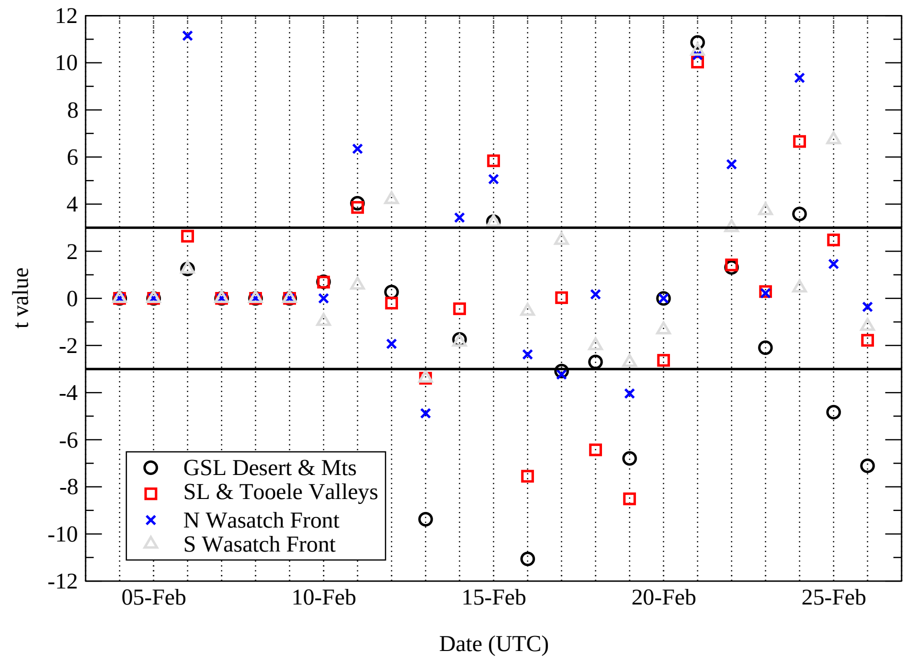


Figure 5.18. Observed and MM5 24-h areal mean and standard deviation for the combined Wasatch Mountains zones. Dates denote the 0000 UTC end time of each 24-h validation period.

(a)



(b)

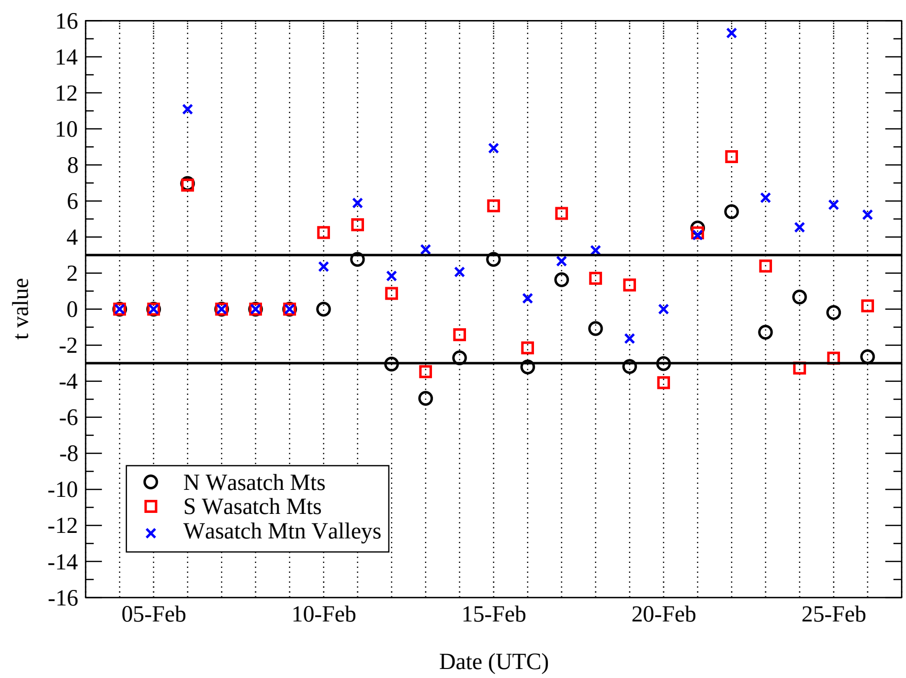


Figure 5.19. Student's t measure of forecast error for the a) Great Salt Lake Desert and Mountains, Salt Lake and Tooele Valleys, Northern Wasatch Front, and Southern Wasatch Front forecast zones; b) Northern Wasatch Mountains, Southern Wasatch Mountains, and Wasatch Mountain Valleys forecast zones; and c) the combined Wasatch Front and Wasatch Mountain zones. Student's t values greater than 3 denote significant overforecasting while values below -3 denote significant underforecasting. Dates denote the 0000 UTC end time of the 24-h validation period.

(c)

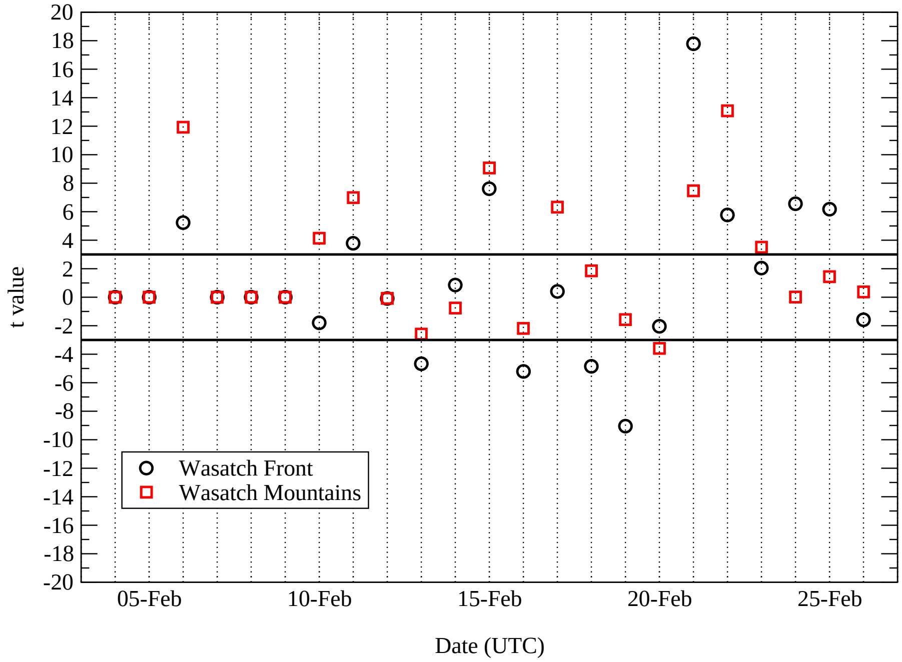


Figure 5.19. (Continued)

Desert and Mountains where significant underforecasting is evident and in the Wasatch Mountain Valleys where precipitation was significantly overforecast. However, the large error in the Great Salt Lake Desert and Mountains may be due in part to the small sample size of available gauges, as well as the biased distribution of surface stations. Large errors are due to both over- and underforecasting in the Salt Lake and Tooele Valleys, although there is a slight tendency for underforecasting. The Northern Wasatch Front has the largest number of forecasts with large errors after the Great Salt Lake Desert and Mountains and Wasatch Mountain Valleys, while the Southern Wasatch Front has the fewest. However, the errors in the Northern Wasatch Front may be affected by the low number of available observations. In the Northern Wasatch Mountains, larger errors are due to underforecasting than overforecasting, while the opposite is true in the Southern Wasatch Mountains.

For the combined Wasatch Front zones, the number of large errors resulting from underforecasting is similar to the number of errors resulting from overforecasting, but there is a slightly greater tendency towards overforecasting. This is due to precipitation being overforecast in the Northern Wasatch Front and Southern Wasatch Front zones, even though precipitation was slightly underforecast in the Salt Lake and Tooele Valleys. For the combined zones of the Wasatch Mountains, the largest errors are due to overforecasting. Even though precipitation was underpredicted in the Northern Wasatch Mountains on five occasions, smaller errors or overprediction in the Southern Wasatch Mountains as well as overprediction in the Wasatch Mountain Valleys serve to decrease the errors in the combined zones such that only one case of significant underforecasting is evident.

To summarize many of the results presented in this chapter, Table 5.2 lists the MM5 model errors during IPEX as a function of climatological zone. Cases in which no precipitation was observed and the model either forecast some, usually minor, precipitation (false alarms) or no precipitation are listed separately. Hence, the sample size of forecasts upon which to judge the MM5 skill is not large and varies between 14 and 16, depending on the climatological zone. The combined Wasatch Front and Wasatch Mountains zones are listed first to reflect the relative confidence that can be assigned based upon the sample size of available gauges and grid points. In other words, the results for the combined zones are likely to be more robust and representative of other periods than the results for some of the individual zones.

The mean difference (1.2 mm) between the forecast and observed precipitation in the Wasatch Mountains combined zones is consistent with the tendency for overforecasting (6 of 16 forecasts are overpredicted). The MM5 exhibits skill for the Wasatch Front combined zones for 7 of the 16 forecasts with no clear trend for under- or overforecasting.

Several obvious tendencies stand out for the individual climatological zones: precipitation in the Northern Wasatch Mountains zone tends to be underforecast while it tends to be overforecast in the Wasatch Mountain Valleys. Besides the Great Salt Lake Desert and Mountains and Wasatch Mountain Valleys, the least skill is evident in the Northern Wasatch Front zone (only 6 of 14 forecasts are skillful); however, the limited number of precipitation gauges in this zone may affect this result. The greatest skill is evident in the Southern Wasatch Front zone (10 of 16 forecasts are skillful).

Table 5.2. Summary of MM5 model error as a function of climatological zone for 23 forecasts during IPEX. The first column denotes the number of 12-36-h MM5 forecasts initialized at 1200 UTC that underpredicted the observed precipitation, the second column denotes the number of skillful forecasts, and the third column indicates the number of overforecasts when precipitation was observed. The fourth column shows the number of times precipitation was forecast yet none was observed (false alarms) and the total number of days when no precipitation was observed. The fifth column shows the time-averaged areal mean observed precipitation. The mean difference between forecast and observed precipitation for all 23 forecasts is listed in the last column.

Zone	Under Forecast	Skillful	Over Forecast	False Alarms/ No Obs. Precip.	Obs Mean (mm)	Mean Error (mm)
Wasatch Front	4	7	5	2/7	2.6	0.2
Wasatch Mountains	1	9	6	2/7	5.3	1.2
GSL Desert and Mts	6	5	3	3/9	3.1	-1.4
SL and Tooele Valleys	4	8	3	2/8	2.6	-0.3
N Wasatch Front	3	6	5	2/9	3.0	0.3
S Wasatch Front	1	10	5	2/7	2.6	0.6
N Wasatch Mts	5	9	2	1/7	6.6	-1.2
S Wasatch Mts	3	8	5	2/7	6.4	1.1
Wasatch Mtn Valleys	0	5	10	2/8	2.6	4.8