Denver International Airport MDSS Demonstration Verification Report for the 2015-2016 Season

Prepared by the

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Introduction

The National Center for Atmospheric Research (NCAR), which is operated by the University Corporation for Atmospheric Research (UCAR), created a custom version of the FHWA Maintenance Decision Support System (MDSS) for Colorado with a specific focus on Denver International Airport (DIA) runway operations. Over the winters of 2012-2015, UCAR and the City and County of Denver, which operates DIA, entered into an agreement for the provision of MDSS services and support to DIA. DIA re-contracted with NCAR to run and support MDSS for three additional seasons, 2016-2018. This is the annual verification report for the DIA MDSS Research and Development Project for the 2015-2016 winter season. This report has two sections, one that examines overall forecast skill by looking at error statics for some key forecast variables over the entire winter season. The other section examines some specific storm event case studies with a focus on MDSS liquid precipitation vs. snowfall forecast, how the forecast changed leading up to the event and bit on and how the human-in-the-loop, i.e. Weathernet influenced the forecast guidance for each case. A summary and future recommendations is given at the end.

Forecast Error Statistics

This section examines MDSS forecast error statistics over the 2015-2016 winter season. RMSE (root mean square error) is plotted for:

- air temperature (T)
- dew point temperature (dewpt)
- wind speed
- cloud cover
- pavement-temperature (road-T).

ETS (equitable threat scores) is plotted for the precipitation rate forecast. ETS is similar to a Critical Success Index which is based on hits, misses, false-alarms and non-events for a given precipitation rate threshold. ETS = (hits - hits expected by chance) / (hits + false alarms + misses – hits expected by chance). More information is given about the ETS score in the Precipitation Forecast Statistics section.

For each of the variables mentioned above there are two plots, one over the entire season, based on all 15z (8am MST / 9am MDT) forecasts generated from November 1, 2015 to April 30, 2016, and another plot that compares the new high-resolution HRRR model to the other components and is based on all 15z forecasts generated from March 1, 2016 to April 30, 2016. Note that the HRRR was added to MDSS at the end of February 2016. For the full season plots, last year’s MDSS-final forecast is also included as a baseline.

Both RMSE and bias are plotted for pavement temperature (road-T) over the entire season. The current stats are based on all 15z forecasts from November 1, 2015 to March 20, 2016 (note that road-T observation data was missing during last part of March and into April). The road-T plots also show a comparison with last season's statistics. On all the plots, lead-time 0 corresponds to 15z (8am/9am), 3 corresponds to 18z (11am/12pm), 6 to 21z (2pm/3pm), 9 to 00z (5pm/6pm), and so on.

The weather statistics (T, dewpt, wind speed, cloud cover) are based on forecasts for all Colorado Plains sites. These consist of 76 sites in eastern Colorado including all observing sites near DIA. For the weather statistics, the plots compare the MDSS-final-forecast to the model components that were used to create the final forecast. The road-T statistics are based on the 3 primary DIA runway sites that had consistent observation data. They were calculated using the recommend road-T forecast. Error characteristics are examined for each variable.

Air Temperature (T) Statistics.

The full-season RMSE plot (figure 1) for T indicates that the MDSS-final-fcst-2015-2016 is better on average than any one of the model components and has average errors of around 2.3 degs C at 24 hours out. The plots also show how forward-error-correcting the forecast greatly reduces the forecast error in the first three hours of the forecast. The MDSS forecast from 2014-2015 is also plotted as a baseline. Note that different weather patterns from one season to the next can impact forecast performance outside any changes to the forecast architecture. Overall the MDSS-final-fcst-2015-2016 has slightly better skill than the equivalent forecast of 2014-2015. The second plot (figure 2) compares the new high-resolution HRRR model to the other components over the time-period it was included in the system. The system was configured to use the first 5 hours of the HRRR forecast so the HRRR plots are zoomed in to just the first 12-hours of the forecast (lead-times 0-12). It is evident that the HRRR is a positive addition for air-T as it exhibits lower RMSE values than most of the input models. Overall the MDSS T forecast shows good skill.

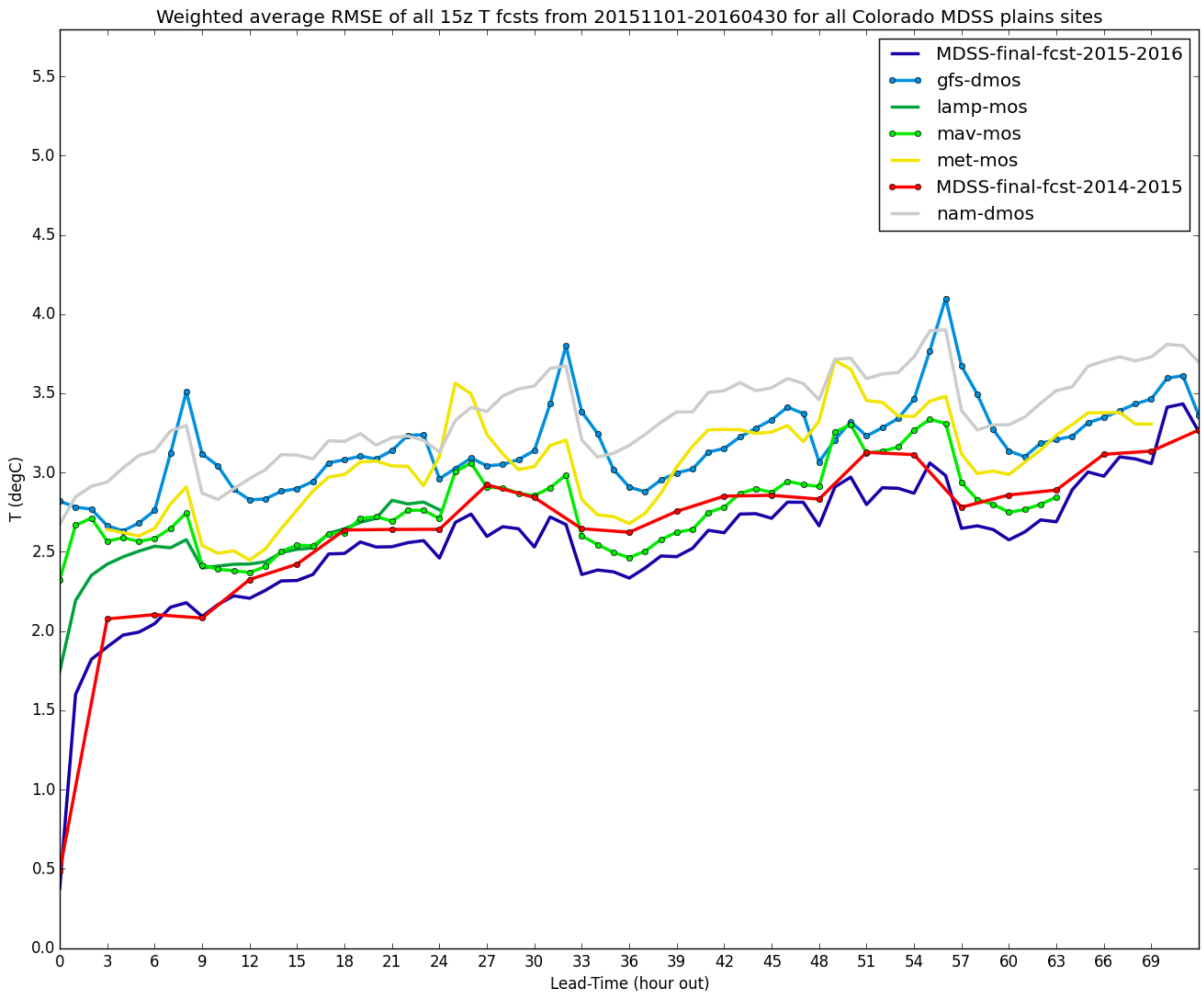

Figure 1: RMSE of air temperature (T) forecast

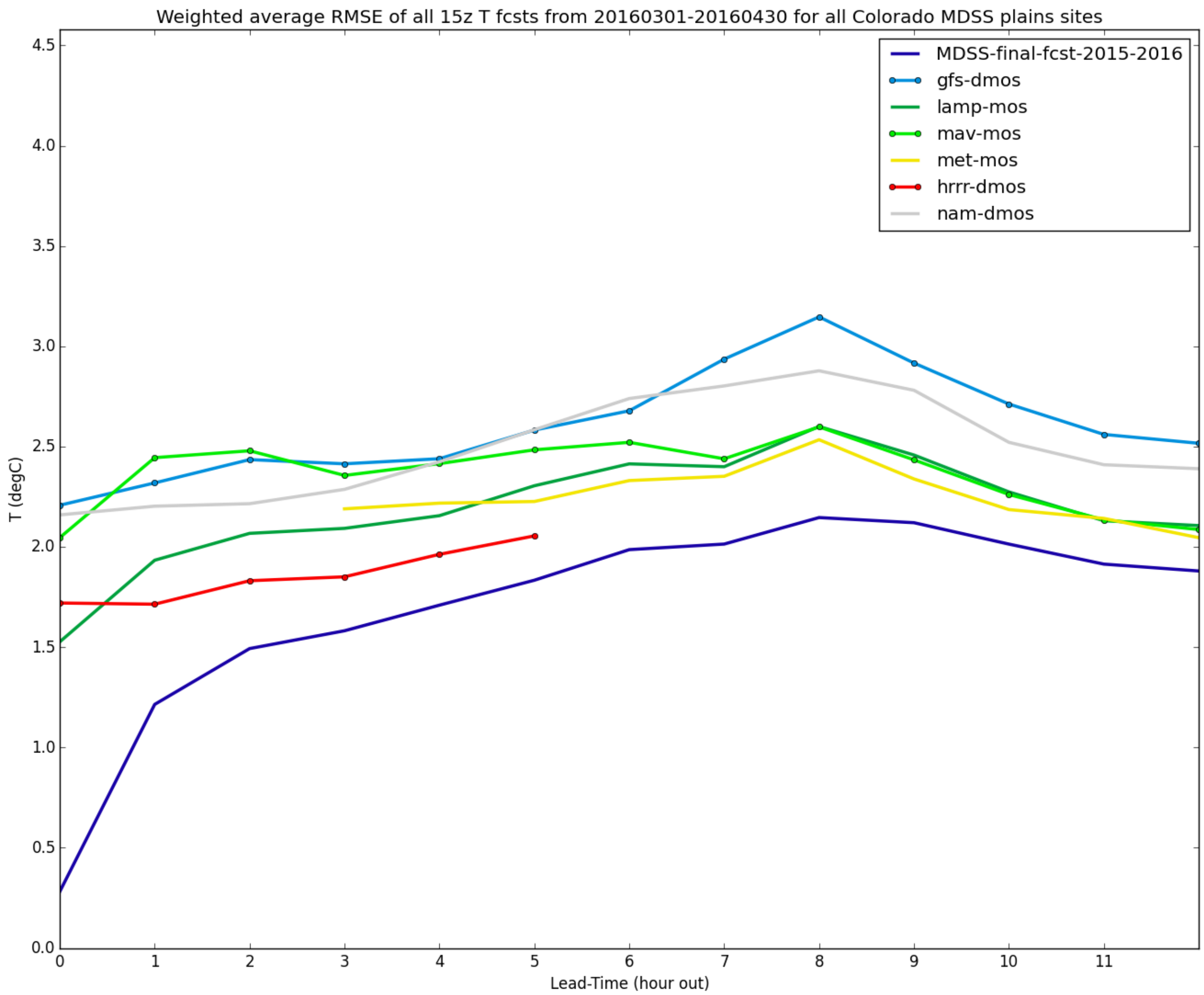

Figure 2: RMSE of air temperature (T) forecast comparing HRRR model

Dew point Temperature (dewpt) Statistics

The full-season RMSE plot (figure 3) for dewpt shows that the MDSS-final-fcst-2015-2016 is better on average than any one of the model components and has average errors of around 2.1 degs C at 24 hours out. The plot also shows how forward-error-correcting the forecast greatly reduces the forecast error in the first three hours of the forecast. Certain model components such as the NAM and GFS show much higher dew point errors during the middle of the day and this contributes to a diurnal change in error characteristics in the final-forecast. The MDSS forecast from 2014-2015 is also plotted as a baseline. Overall the MDSS-final-fcst-2015-2016 has slightly better skill than the equivalent forecast of 2014-2015. The second plot (figure 4) compares the new high-resolution HRRR model to the other components over the time-period for which it was included in the system. The plot shows that the HRRR has fairly low error values compared to the other NWP models (such as NAM and GFS) but is not as good as some of the MOS components (LAMP and MET are better). Overall the MDSS dewpt forecast shows good skill.

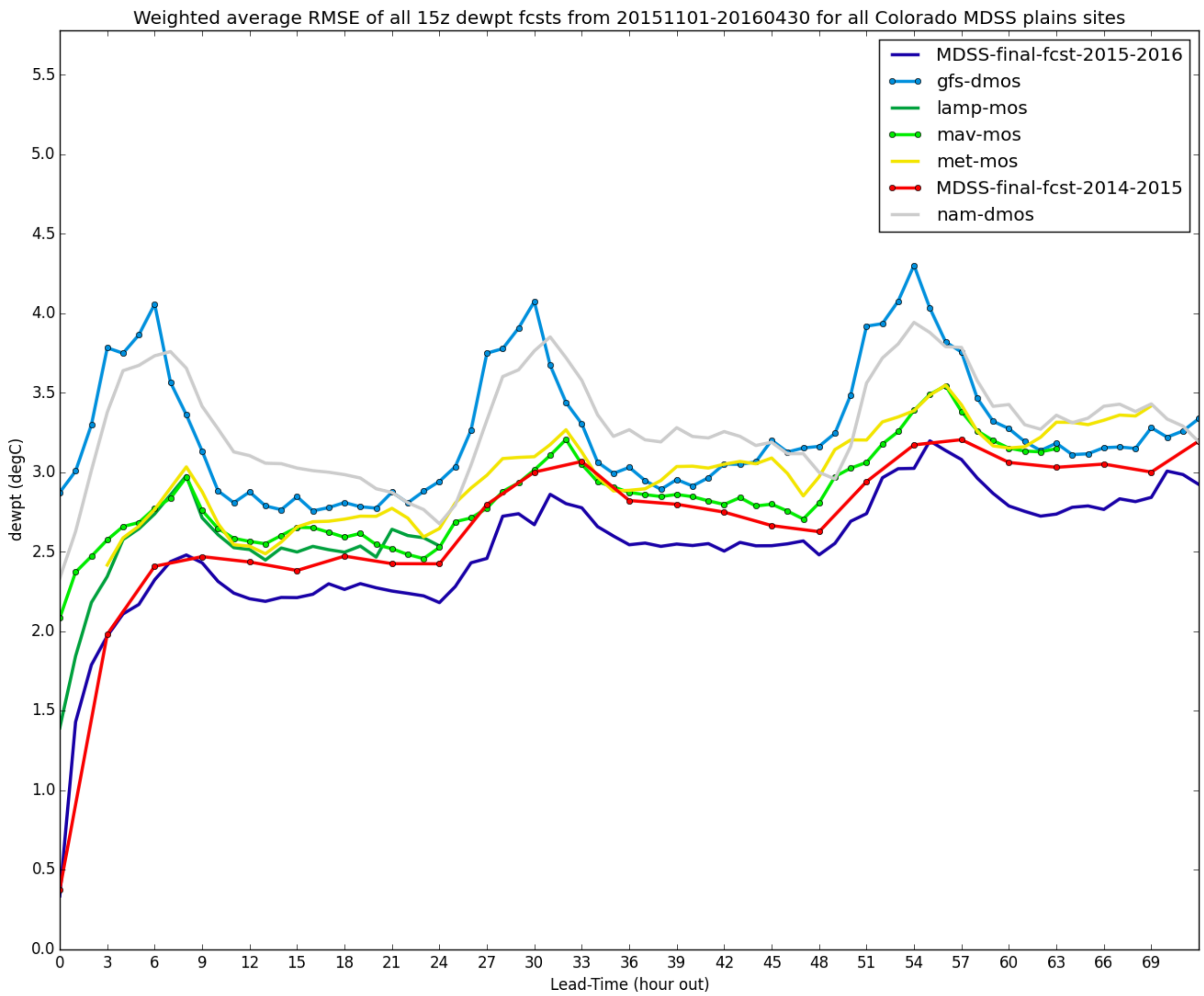

Figure 3: RMSE of dew point temperature (dewpt) forecast

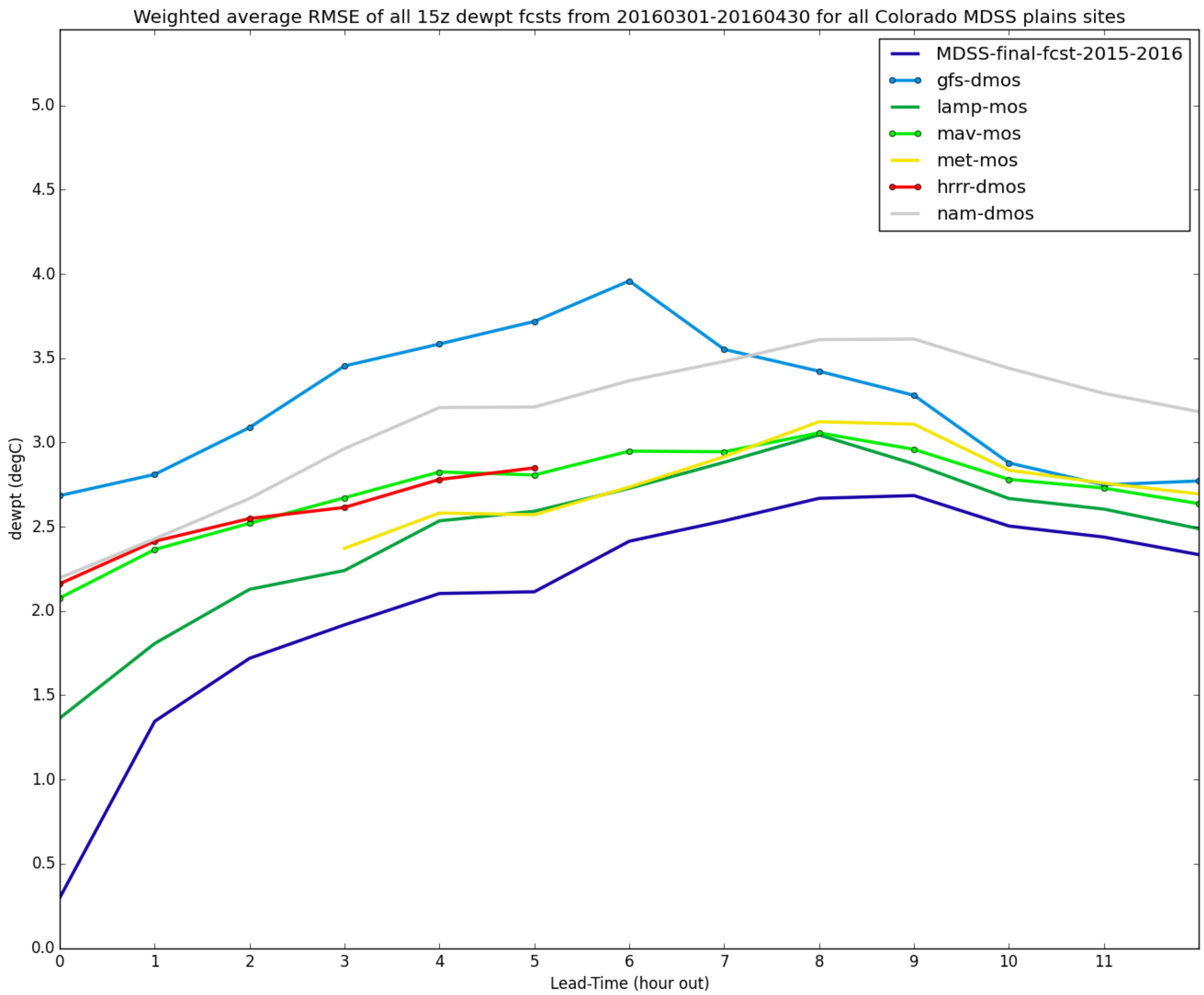

Figure 4: RMSE of dew point temperature (dewpt) forecast comparing HRRR model

Wind Speed Statistics.

The full-season RMSE plot (figure 5) for wind speed shows that the MDSS-final-fcst-2015-2016 is better on average than any one of the model components and has average errors of around 2 m/s at 24 hours out. The plot also shows how forward-error-correcting the forecast reduces the forecast error in the first three hours of the forecast. The MDSS forecast from 2014-2015 is also plotted as a baseline. For wind speed in particular, the error statistics from this year's MDSS wind speed forecast show higher errors on average compared to last year. Most of the difference can be attributed to the fact that there were more winter storms this year and thus more variable / challenging wind conditions to forecast, which leads to higher forecast errors. Also some of the MOS components, such as LAMP and MAV have much higher relative forecast errors for wind speed than they do for T and dew point and this also contributes to some higher errors in the MDSS final forecast. The second plot (figure 6) compares the new high-resolution HRRR model to the other components over the time-period for which it was included in the system. The system was configured to use the first 5 hours of the HRRR forecast so the second plot is zoomed in to just the first 12-hours of the forecast (lead-times 0-12). For wind speed the HRRR shows decent skill and is equivalent to the other NWP models such as the NAM and GFS. Overall the MDSS wind speed forecast shows good skill relative to the other models.

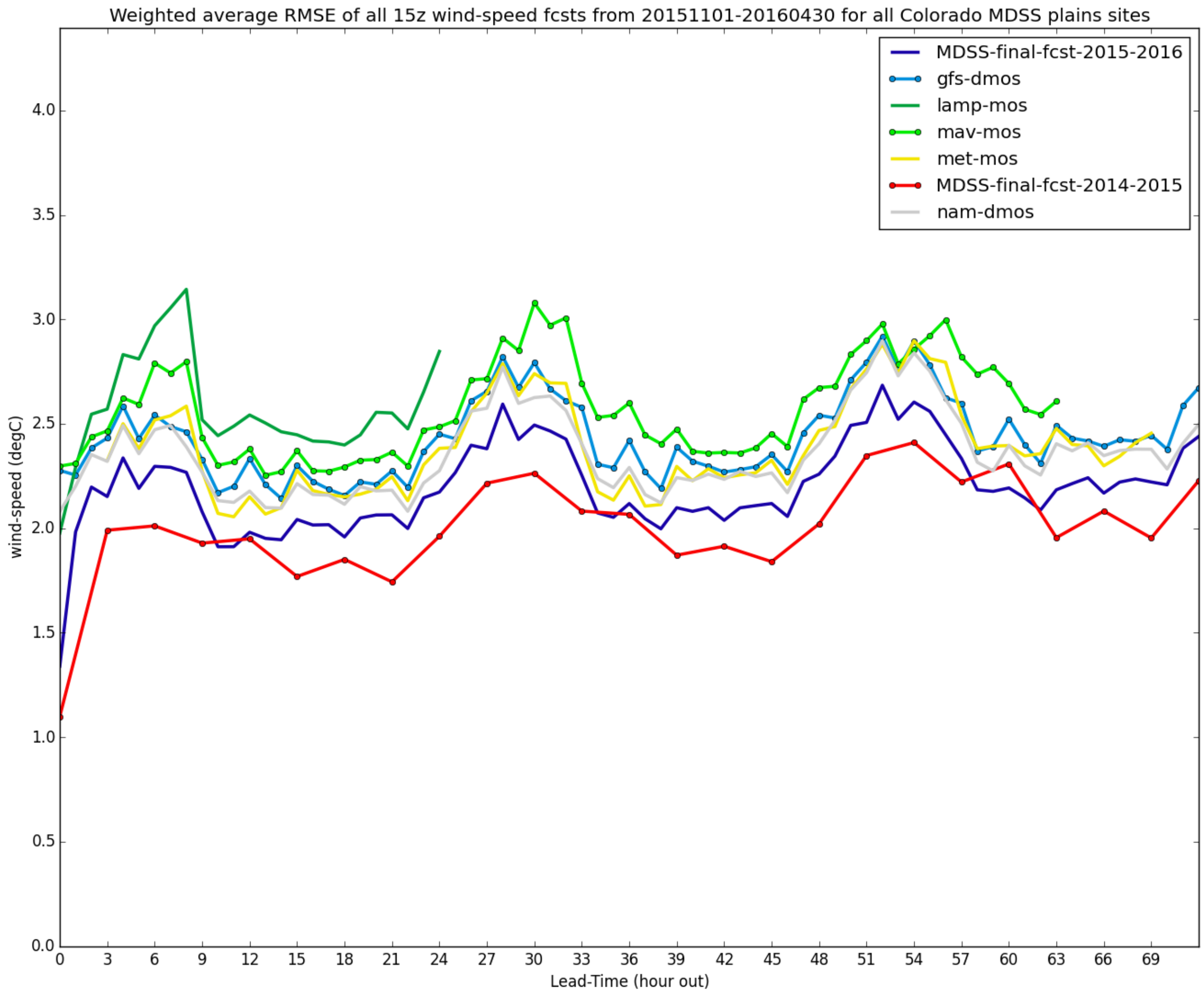

Figure 5: RMSE of wind speed forecast

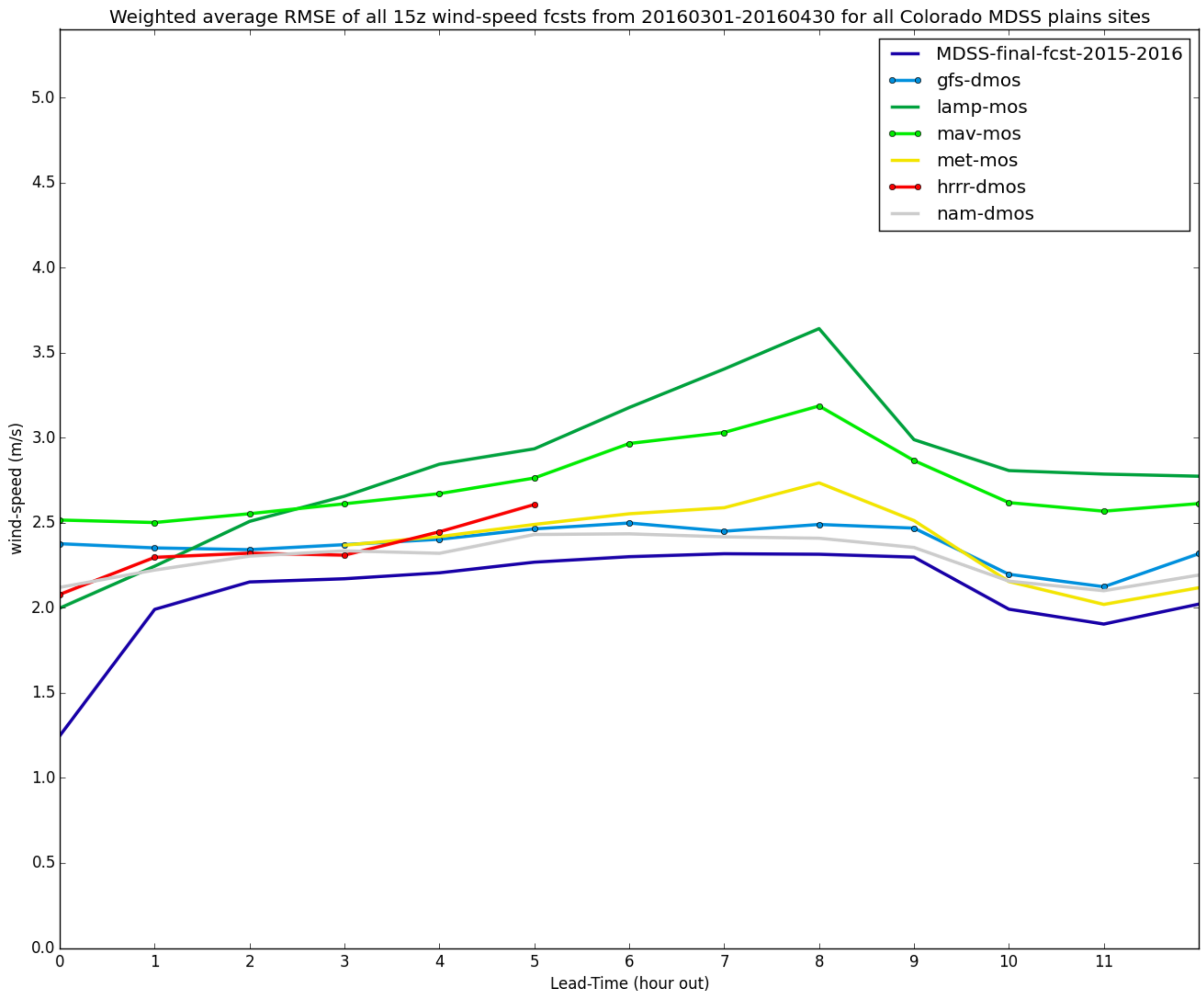

Figure 6: RMSE of wind speed forecast comparing HRRR model

Cloud Cover Statistics.

For this season's verification report cloud cover forecast statistics are examined because the cloud cover forecast is one of the main drivers of the pavement-temperature forecast. The pavement model in MDSS called METRO uses cloud cover to estimate short-wave radiation hitting the surface of the road, and this is a big factor in determining the pavement temperature. The full-season RMSE plot (figure 7) for cloud cover shows that the MDSS-final-fcst-2015-2016 is significantly better on average than any one of the model components and has an average error of around 27 percent at 24 hours out. The plots also show how forward-error-correcting the forecast reduces the forecast error in the first three hours of the forecast.

In general the MOS components (LAMP, MAV and MET) have the best cloud cover skill relative to the other model components. The GFS was not included in the plots because of missing cloud cover forecast for a large time-period after the GFS was upgraded in January. The GFS is now producing cloud cover forecast and cloud cover stats for it will be included in next years' verification report. The second plot (figure 8) compares the new high-resolution HRRR model to the other components over the time-period for which it was included in the system. The system was configured to use the first 5 hours of the HRRR. For cloud cover the HRRR exhibits slightly worse skill on average than the other model components, especially compared to the MOS components. This is not surprising considering the HRRR is a cloud / thunderstorm resolving model and sometime prior to precipitation actually occurring, it puts the clouds in the wrong spot and thus can have more dramatic spatial forecast errors.

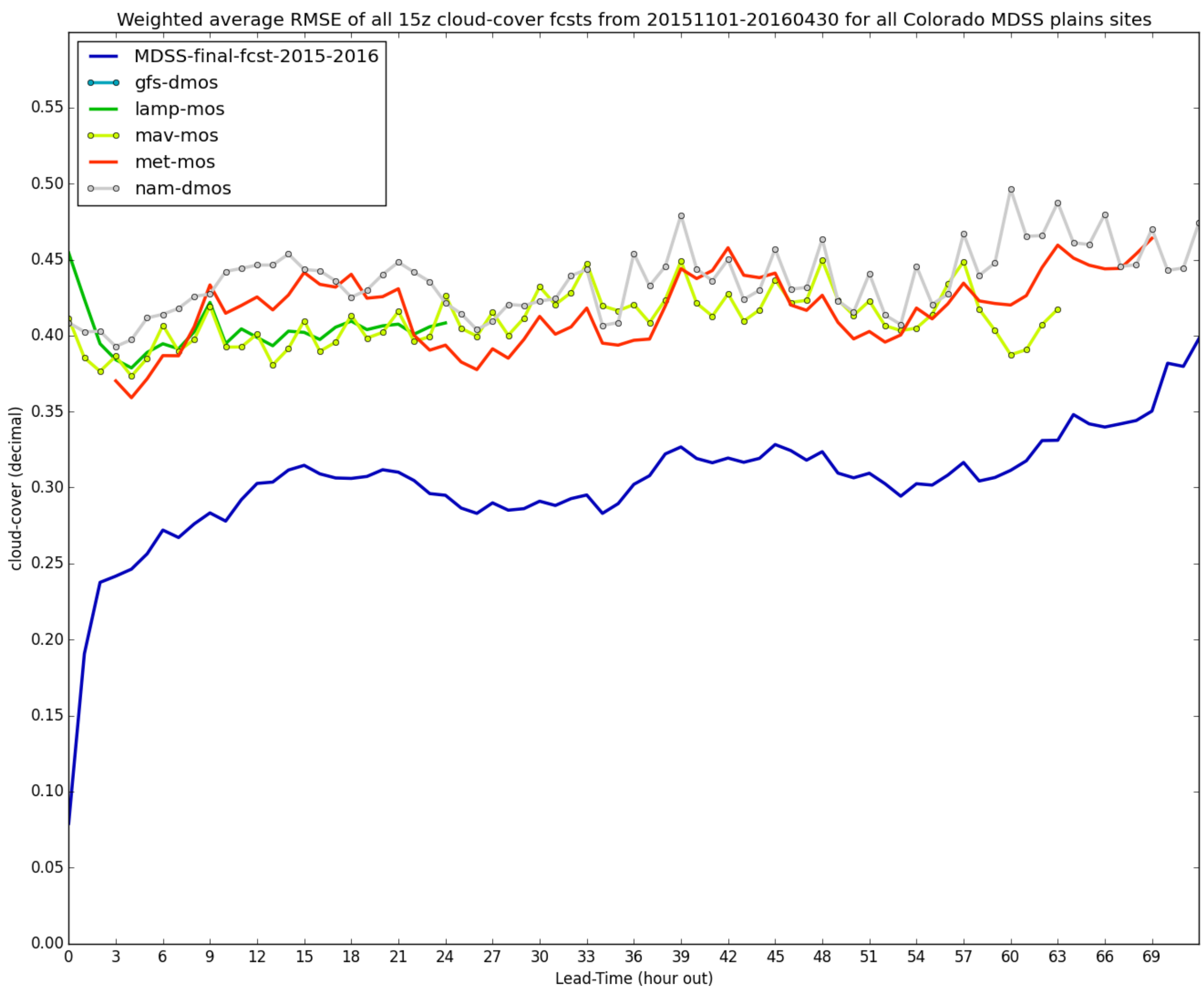

Figure 7: RMSE of cloud cover forecast

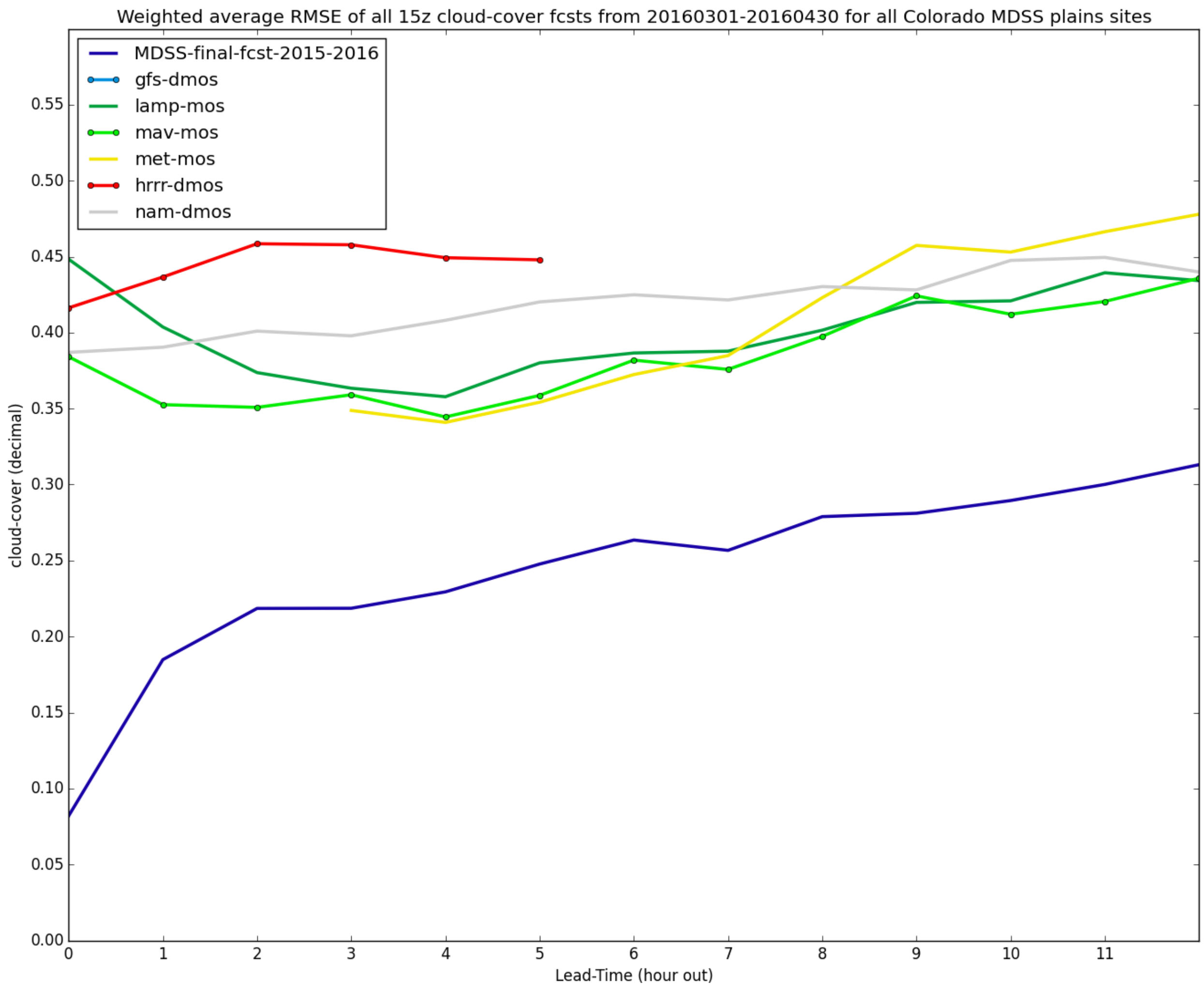

Figure 8: RMSE of cloud cover forecast comparing HRRR model

Pavement Temperature (road-T) Statistics.

The RMSE plot (figure 9) for road-T shows a strong diurnal pattern in forecast error. The road-T forecasts have higher errors during the afternoon (hours associated with peak heating of the pavement). During the middle of the day, the road-T forecast have errors that are on average around 4 degC. The forecast errors are considerably less during the evening, overnight and morning hours, with an average error of 1.7 degC during those times. A comparison to last season's forecast statistics shows that the road-T errors are lower on average this season compared to last season. The improvement is likely due to some small improvements in the weather forecast, some small improvements / bug-fixes in the road-condition-treatment module but also likely due to just different weather patterns from one season to the next. Figure 10 compares this season's average bias values to last season's values. It's obvious that the larger errors during the day are related to a cold-bias in the forecast during the middle of the day. Compared to last year, this year's bias values are lower (less bias) but there is still the same diurnal pattern with a systematic cold-bias during the middle of the day / afternoon. During next winter season, parts of MDSS will be examined to see if the cold-bias can be reduced during the day. Overall the MDSS road-T forecast seems to perform decently during precipitation events (based on analysis of past case studies), but shows less skill predicting road-T during non-storm conditions and during warmer time-periods (such as peak heating and also during fall and spring when there is more radiation and warmer air temperatures).

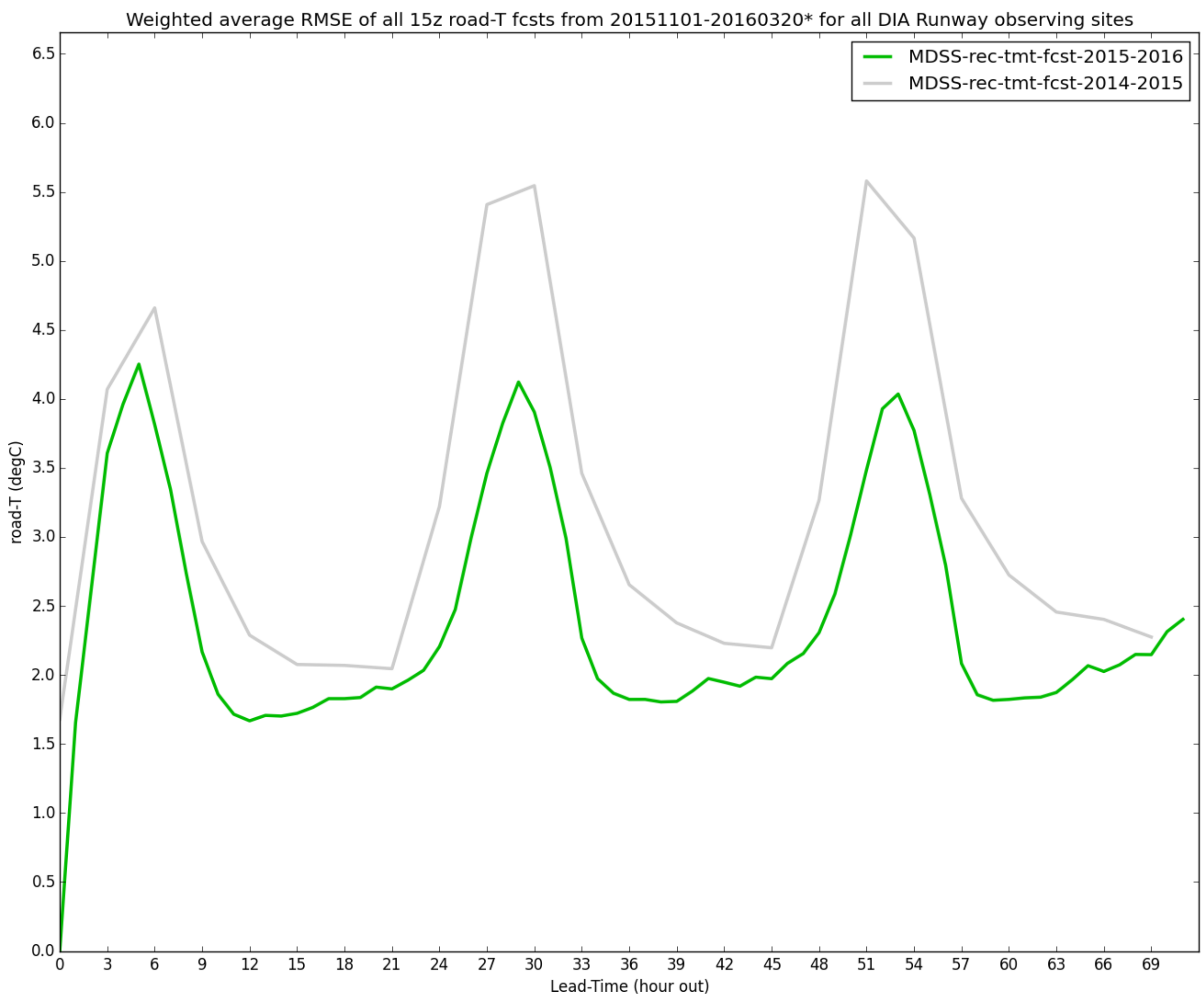

Figure 9: RMSE of pavement-temperature (road-T) forecast

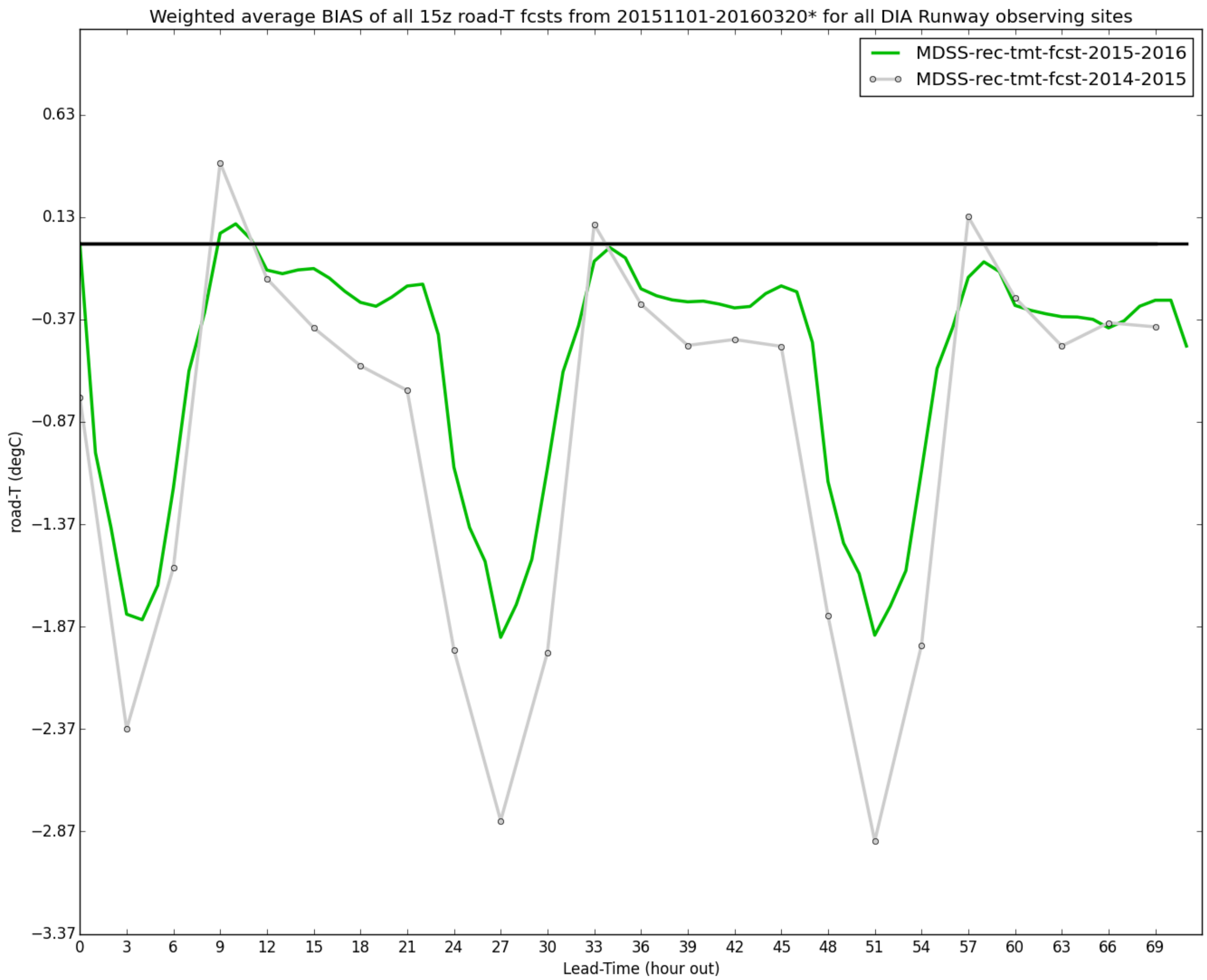

Figure 10: Bias of pavement-temperature (road-T) forecast

Precipitation Forecast Statistics

For this year's verification report the MDSS liquid precipitation forecast skill is examined using Equitable Threat Score (ETS) statistics. ETS is similar to a Critical Success Index which is based on hits, misses, false-alarms and non-events for a given precipitation rate threshold. ETS = (hits - hits expected by chance) / (hits + false alarms + misses – hits expected by chance). Basically the statistic is related to how often a model correctly forecasts a precipitation rate that is at or higher than a given precipitation rate threshold. The plots below look at ETS scores per lead-time for two different precipitation rate thresholds, 0.254 mm (0.1 inches) and also 0.508 mm (0.2 inches). The 0.1 inches/hour would be equivalent to a 1 inch/hour snow-rate (10:1 ratio) and the 0.2 inch/hour would be equivalent to a snow rate of 2 inches per hour. So for example the ETS plot for 0.1 inches indicates how often the model correctly predicted a liquid precipitation rate of 0.1 inches/hour or higher per lead-time (based on all 15z forecasts throughout the entire season). Higher ETS values indicate better skill (more hits, less false alarms, etc.). It should be noted that the MDSS precipitation forecast is based on a statically weighted combination of the NWP models in the system (MOS products are not used because they don't explicitly give hourly precipitation rate). There are two plots for each threshold, one over the entire season, and another plot over the last two months that compares the new high-res HRRR model to the other models used for precipitation prediction in MDSS. The full-season ETS plot for both the 0.254mm and 0.508mm thresholds (figures 11 and 12) show that the MDSS-final-fcst-2015-2016 is better on average than the model components used for the precipitation forecast; it has higher ETS scores than the GFS and NAM. Overall the GFS exhibits higher ETS scores than the NAM. The second set of plots (figures 13 and 14) compares the new high-resolution HRRR model to the other components over the time-period for which it was included in the system. The system was configured to use the first 5 hours of the HRRR forecast so these plots are zoomed in to just the first 12-hours of the forecast (lead-times 0-12). Both of the plots show that the HRRR has good skill predicting precipitation (higher ETS values) during the first 3-5 hours of the forecast and this contributes to better skill from the final MDSS forecast (when the HRRR is in the mix). The HRRR was specifically designed to do a much better job resolving short-term precipitation such as more accurately predicting the start time for a big snow event, when an intense snow-band will occur and also when and where convection (thunderstorms) will occur. After examining ETS scores during the spring, the MDSS static model combination for its precipitation forecast was adjusted to use predominantly the HRRR (when it's available) and then mostly GFS and then some NAM. The current model weights for the precipitation forecast are: 60% HRRR, 30% GFS and 10% NAM, when the HRRR drops out (after 6 hours), the weights go to 75% GFS and 25% NAM. Overall this combination gives the MDSS final-forecast more skill than any one of the model components for predicting hourly precipitation rate.

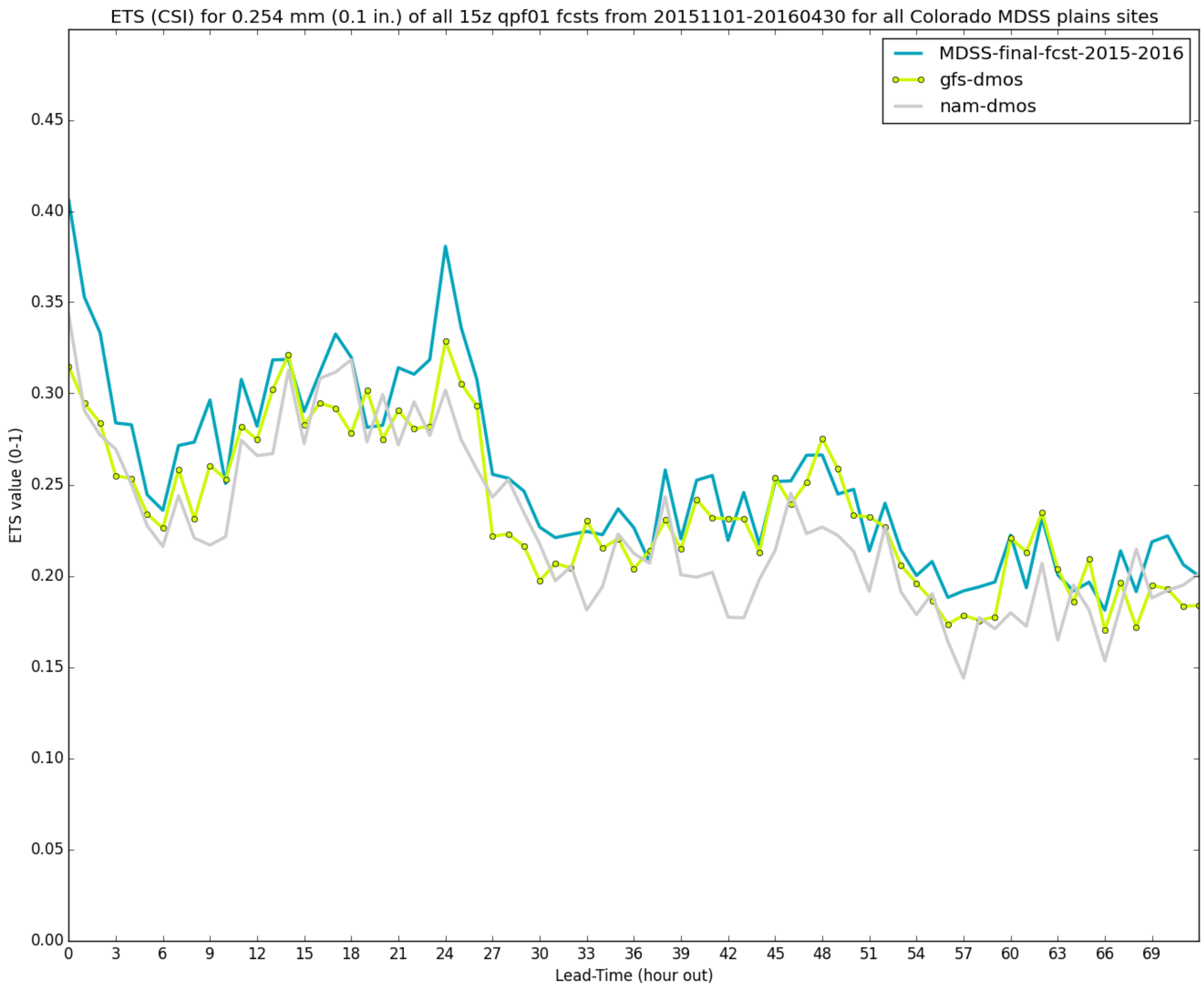

Figure 11: ETS values for liquid precipitation rate threshold of 0.254 mm (0.1 inches)

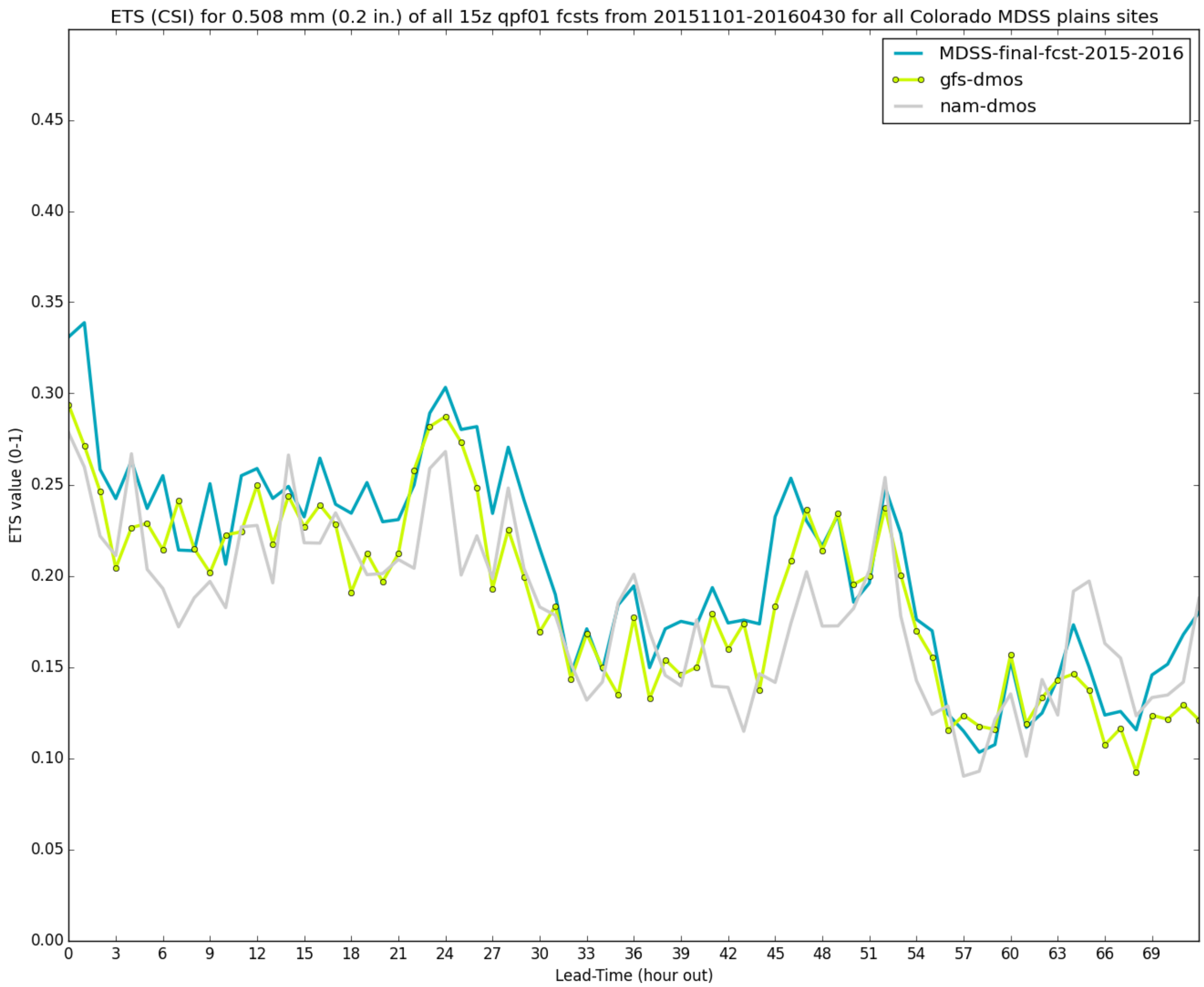

Figure 12: ETS values for liquid precipitation rate threshold of 0.508 mm (0.2 inches)

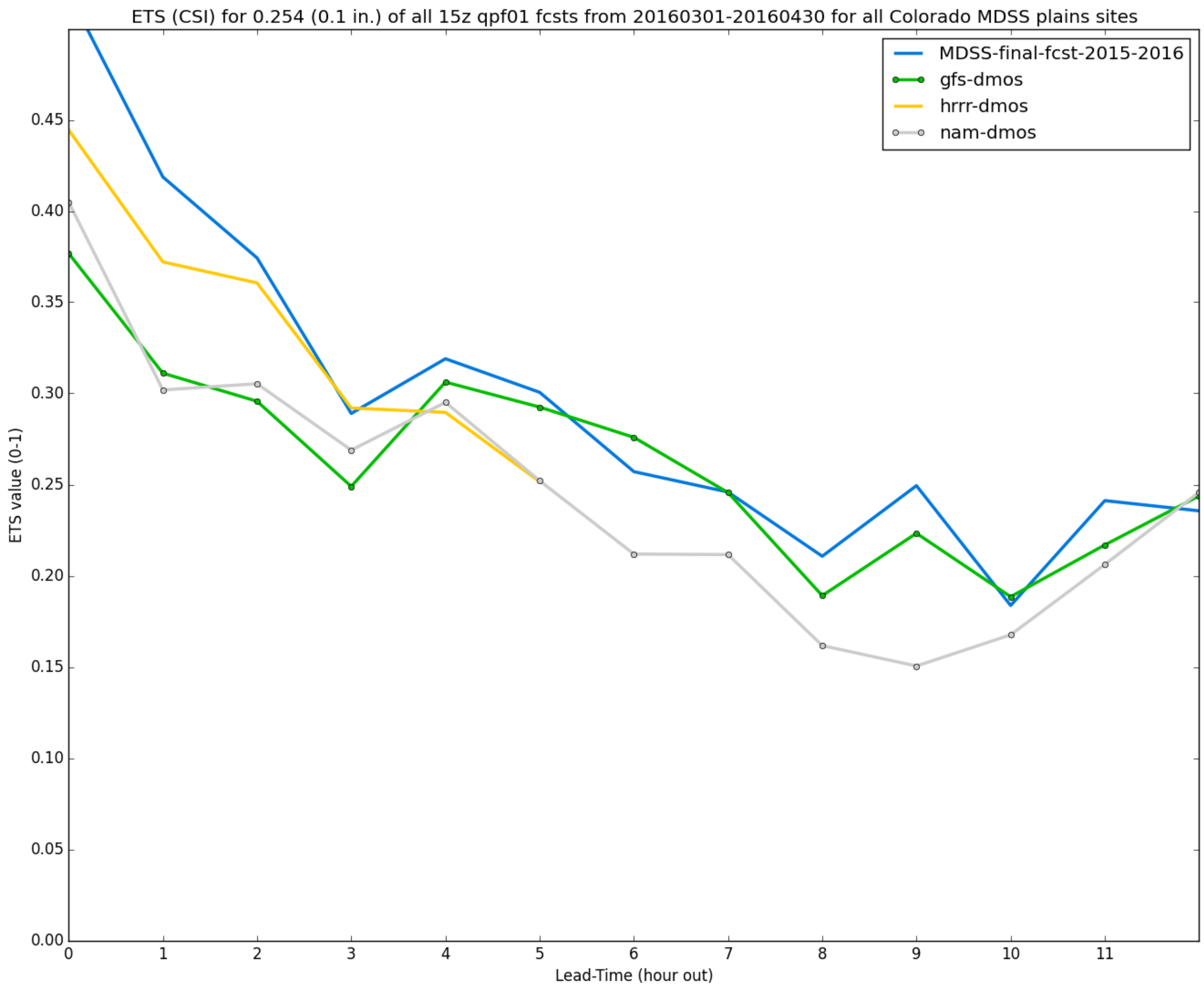

Figure 13: ETS values for liquid precipitation rate threshold of 0.254 mm (0.1 inches) comparing HRRR model

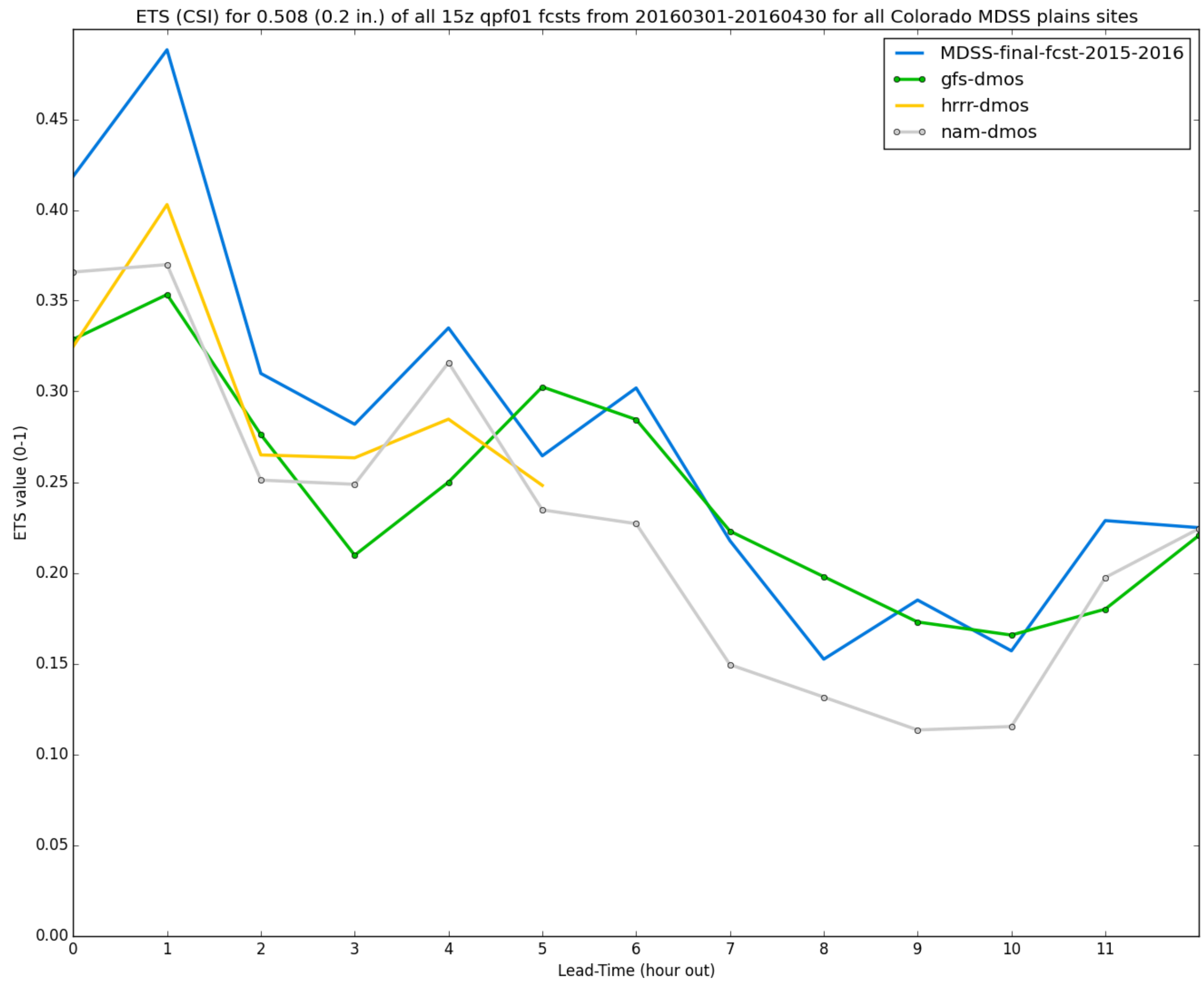

Figure 14: ETS values for liquid precipitation rate threshold of 0.508 mm (0.2 inches) comparing HRRR model

Storm Event Case Studies

This section will look at some storm event case studies and highlight some unique aspects specific to each case. The focus for this years' report is the MDSS liquid precipitation forecast and the derived snowfall forecast for each event. For two of the cases in spring, multiple MDSS forecasts leading up to the event are examined, one that is further out (12+ hours) from the start time and another forecast that is much closer (within about 6 hours) of the start time so the influence of the high-resolution HRRR model can be examined to see how it changes the MDSS precipitation forecast. The human in the loop forecast, i.e. from Weathernet will also be examined for each event. For each case there is a table that shows the MDSS total liquid precipitation forecast(s), the MDSS total snowfall forecast(s), the Weathernet total snowfall forecast(s) and the observed total liquid precipitation and snowfall recorded at DIA (listed as the official totals for Denver from the Denver/Boulder National Weather Service climate page). Plots of the forecast total liquid precipitation are also included for each event. The plots compare the total-precipitation forecast from MDSS and its model components to the total liquid precipitation observed by the KDEN METAR (ASOS) site. It should be noted that the METAR site typically under-catches liquid precipitation during intense snow-events and that will be discussed a little more in the cases below. Note that local times (MST or MDT) are used in some of the case descriptions but the time-series plots use UTC. 17z corresponds to 10am MST, 21z to 2pm MST and 03z to 2am MST.

Case: December 14-15, 2015. Winter snow event with moderate temperatures.

The December 14-15 event can be characterized by a classic winter storm with moderate temperatures. This was the first significant snow-storm of the season for the Denver/Boulder area. Much of the western suburbs picked up 10-15" of snow from this event. The official numbers from DIA were 7.7" of snow but only 0.32" of liquid (that would be a snow ratio of 24:1) and this indicates that the METAR site (KDEN) likely did not properly measure the liquid amount from this event. It should be noted that METAR sites (ASOS, AWOS) typically under-catch liquid precipitation during big snow events and this appears to be the case here. This is also mentioned as an issue for the other cases presented below. The MDSS forecast about 12 hours before the event, issued on December 14th at 17z (10am) called for 0.56" of liquid and 3.8" of snow. The forecast liquid amount from MDSS was quite good for this event as the observed amount should have been closer to 0.6" of liquid (based on a more realistic snow ratio of 13:1) Looking into the forecast details, MDSS was too warm with forecast air temperatures on the morning of December 15th and thus had a snow ratio that was way to low (7:1 at 4am and down to 4:1 at 7am) and this caused a low snowfall forecast. Looking at the forecast total-precipitation graph (figure 15) shows that the NWP models and MDSS were quite good with the initial precipitation rate / intensity but were about 3 hours early with the start time. The MDSS forecast total-precipitation was between that of the NAM which was too high for this event and that of the GFS which was closer to what was observed. Note that the system was using an old configuration for the static precipitation forecast weighting for this event (refer to Precipitation Statistics section above for new weights). The Weathernet forecast issued at 10am on December 14th called for 3-5" of snow and this was a bit less than what was recorded at DIA but still indicated that there would be impacts on the runway due to snow and ice; so the guidance was good in conjunction with the MDSS forecast even though both under estimated the snowfall. Overall, MDSS did well predicting the liquid amount for this event but did not do well predicting the total snowfall and that was related to using too low of a snow ratio.

December 14-15, 2015		
	Total Liquid Precipitation (inches)	**Total Snowfall (inches)**
MDSS Forecast 20151214 17z	**0.56**	**3.8**
Weathernet Forecast 20160415 17z	**NA**	**3-5**
Observed / Measured Totals (KDEN, DIA)	**0.32**	**7.7**

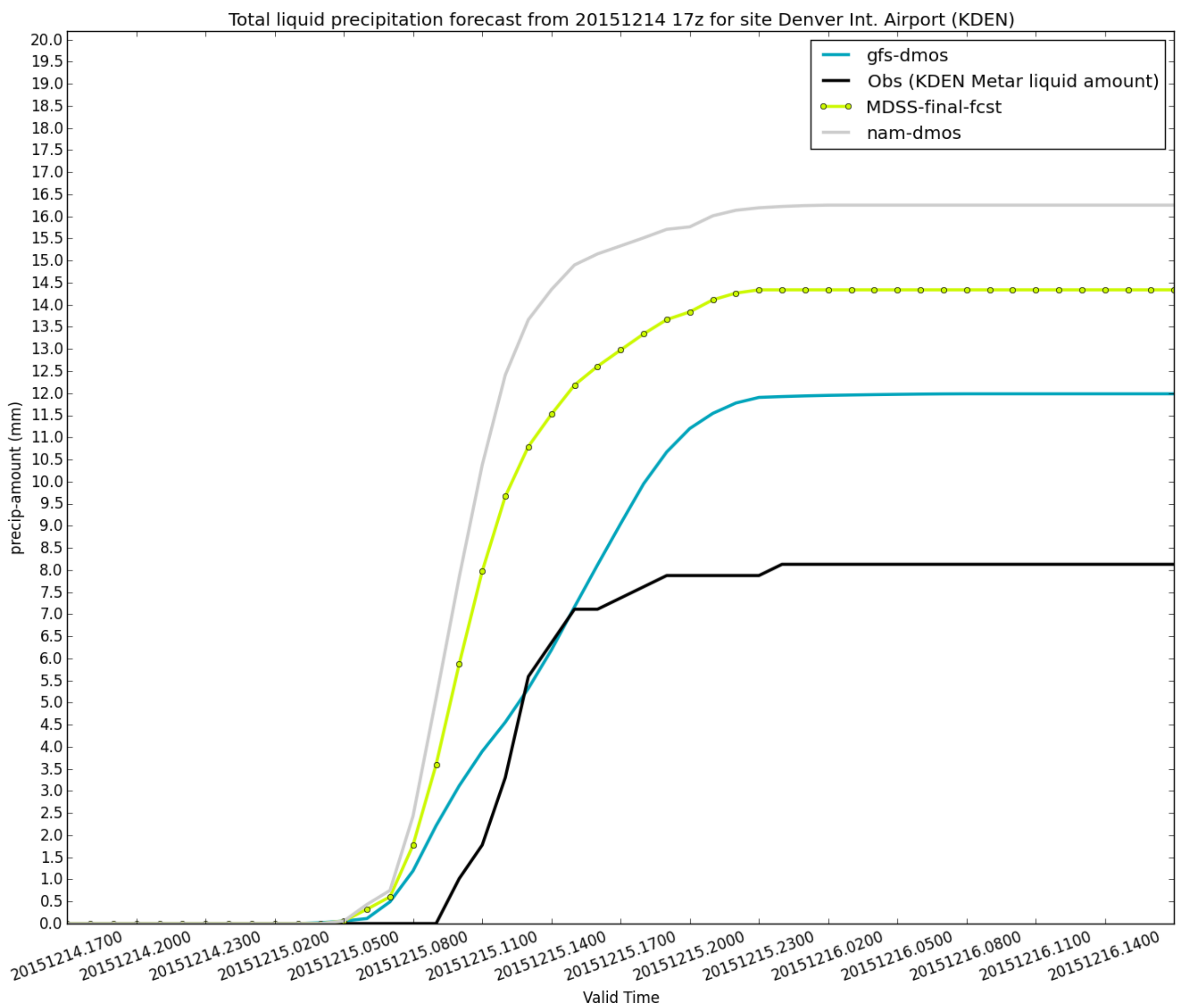

Figure 15: Total liquid precipitation forecast from 10am (17z) on December 14, 2015

Case: March 22-23, 2016. Heavy spring snow event.

The March 22-23 winter storm was the largest and most intense snow storm of the season for DIA and the rest of the Denver/Boulder area. The 13.1" recorded at DIA was the highest single snowfall total of the season. Parts of the western suburbs picked up a whopping 20-24" of snow from this event. Most of the snow fell in a short but intense window during the morning and day-time hours on March 23rd. One aspect of this event that is important to note for verification is that the METAR site at DIA (KDEN) severely under-measured the liquid precipitation for this event. The Denver/Boulder National Weather Service office put out an official statement regarding this event. "THE MARCH 23RD PRECIPITATION HAS BEEN ADJUSTED FROM 0.49 TO 0.77. THE 0.77 WAS MEASURED BY THE OFFICIAL DIA SNOW OBSERVERS APPROXIMATELY 1 MILE TO THE SOUTHWEST OF THE ASOS. IT IS LIKELY THAT THIS AMOUNT IS TOO LOW DUE TO UNDERCATCH FROM BLIZZARD. SURROUNDING OBSERVATIONS SUGGEST THE VALUE SHOULD BE CLOSER TO 1.35 INCHES." So in the table and precipitation-total graphs below, the 1.35" is used as the observed total from DIA. The MDSS forecast about 12 hours before the event, issued on March 22nd at 21z (2pm) called for 1.25" liquid but only 2.9" of snow. Deeper examination, reveals that MDSS forecast was predicting air temperatures of 38-40 degF during the morning and day on March 23rd, whereas the observations show that the air temperatures were really between 28-30 degF. So the initial MDSS forecast had more rain than snow and even when it was predicting snow it had a liquid to snow ratio that was way too low (3:1), likely due to the predicted warm air-temps. The NWP models really struggled leading up to this event as far as air temperatures and total precipitation amounts. Figure 16 shows that the initial MDSS forecast did a good job predicting the total precipitation amount. If the snow ratio would have been higher it would have more accurately predicted the correct snowfall. The MDSS forecast did improve somewhat closer to the event starting. The forecast about 1-2 hours before heavy snow started, issued on March 23rd at 09z (2am) called for 1.6" liquid and 5.0" of snow. Again, MDSS under-forecasted the snowfall due to warm air-temps and too low of a snow ratio. Figure 17 shows that the high-resolution HRRR model did help predict the initial start time and precipitation intensity on the morning of March 23rd. The Weathernet forecast issued at 10am on March 22nd called for just 2-4" of snow but by 4am on March 23rd, they were calling for 4-8" of snow. Even though the Weathernet forecasts were still too low, it was closer to the observed total snowfall than what was predicted by MDSS. This was an event that was initially poorly forecast by the NWP models and thus the MDSS and Weathernet forecasts struggled, especially the day before the event. Overall the MDSS liquid precipitation forecast was good but the snow ratio could be improved for this type of event.

March 22-23, 2016		
	Total Liquid Precipitation (inches)	Total Snowfall (inches)
MDSS Forecast 20160322 21z	1.25	2.9
MDSS Forecast 20160323 09z	1.6	5.0
Weathernet Forecast 20160322 17z	NA	2-4
Weathernet Forecast 20160323 11z	NA	4-8
Observed / Measured Totals (KDEN, DIA)	1.35*	13.1

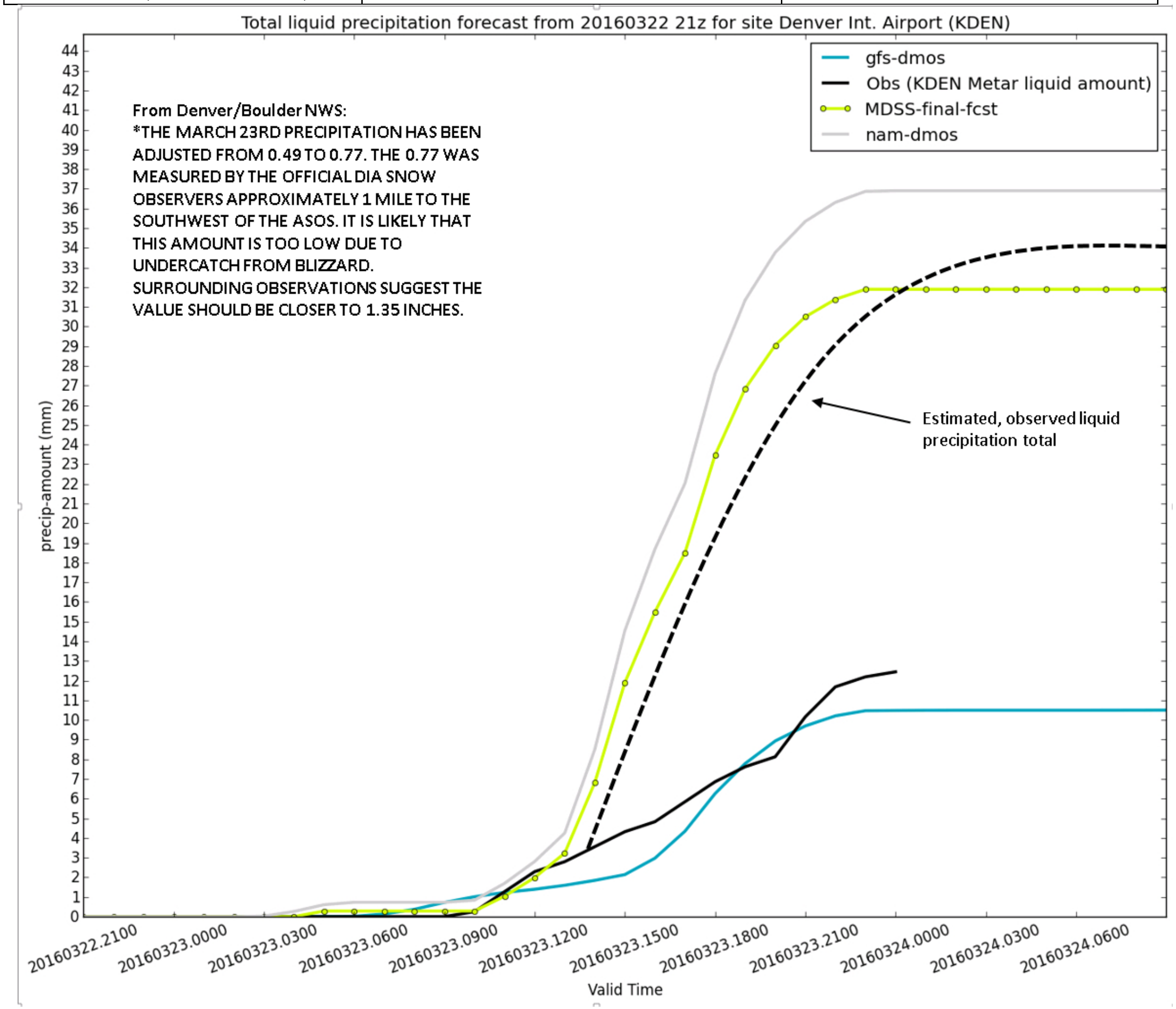

Figure 16: Total liquid precipitation forecast from 2pm (21z) on March 22, 2016

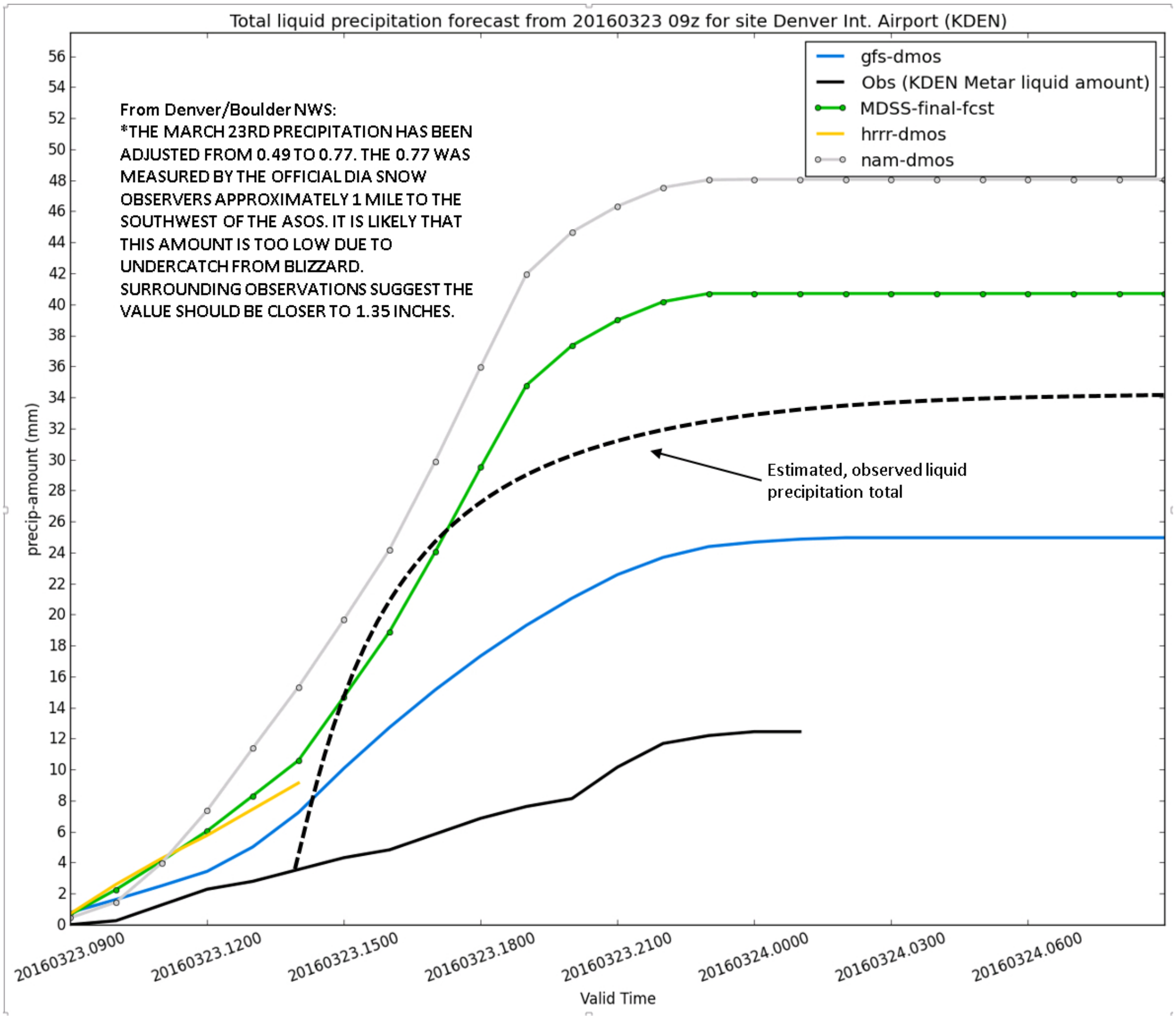

Figure 17: Total liquid precipitation forecast from 2am (09z) on March 23, 2016 to compare HRRR model

Case: April 16-17, 2016. Wet spring snow event.

The April 16-17 winter storm was another large spring storms system. The storm can be characterized by a wet event with rain changing to snow and borderline temperatures for snowfall accumulation. The 12.1” recorded at DIA was the second highest storm total of the season. Parts of south Denver picked up 18” of snow and parts of the foothills west of Denver/Boulder picked up over 40” of snow from this event. The official liquid precipitation-total from the KDEN METAR was 1.39”. It should be noted that the observed liquid amount is likely lower than what actually fell and was likely closer to 1.8” of liquid based on surrounding observations. As mentioned earlier, METAR sites typically under-catch liquid precipitation during big snow events. The MDSS forecast about 12 hours before the event, issued on April 15th at 21z (2pm) called for 2.55” of liquid but only 2.3” of snow. This initial forecast showed relatively warm air temperatures and was calling for much more rain than snow and thus the snowfall forecast was too low. Looking at the April 15th, 21z forecast total precipitation graph (figure 18), the NWP models components and MDSS over forecasted the liquid precipitation amount and also had the event starting about 6 hour before the actual start time. The MDSS snowfall forecast did improve significantly closer to the start of the event especially as it came under the influence of the high-resolution HRRR model. The MDSS forecast from April 16, 09z (2am) called for 2.12" of liquid and 9.0" of snow, which was much closer to the observed snow-total of 12.1". The total precipitation graph from this forecast (figure 19) shows that the HRRR really helped get the initial precipitation rate and intensity and with the MDSS forecast weighted towards the HRRR, its precipitation rate closely followed the observed precipitation rate through the first 12 hours of the event. Ultimately the models, including MDSS, over-forecasted the total precipitation amount but were likely closer than what was indicated in the graph (figure 19), due to under-catch at the METAR site. Looking more into the April 16th 09z forecast, MDSS was still forecasting air temperatures that were warmer than what was observed and this contributed to the MDSS using a snow ratio that was too low. The 9.0" of snow that it forecast was quite good compared to what was observed, but if the correct snow ratio had been used during the brunt of the event, MDSS would have forecast much more total snowfall. So this is another case where the snow ratio could be improved. Looking at the human in the loop for this event, the Weathernet forecasts for this event were quite good. The Weathernet forecast issued at 10am on April 15th called for 7-10" of snow. Their updated forecast issued at 4pm on April 16th called for an additional 4-8" of snow with a snow total of 8-15" at DIA. Overall the Weathernet guidance helped for this case as the initial MDSS snowfall forecast was too low (2.3") and Weathernet called for 7-10" of snow which was close to the observed about of 12.1". The event ended earlier than expected at DIA so the updated Weathernet forecast called for a bit more snow than actually fell but was still quite close to what was observed and the forecast properly reflected that this would be a cold and impactful event. Overall the MDSS and Weathernet forecasts were good for this event.

April 15-16, 2016		
	Total Liquid Precipitation (inches)	**Total Snowfall (inches)**
MDSS Forecast 20160415 21z	**2.55**	**2.3**
MDSS Forecast 20160416 09z	**2.12**	**9.0**
Weathernet Forecast 20160415 17z	**NA**	**7-10**
Weathernet Forecast 20160416 23z	**NA**	**Additional 4-6, with a total of 8-15**
Observed / Measured Totals (KDEN, DIA)	**1.39**	**12.1**

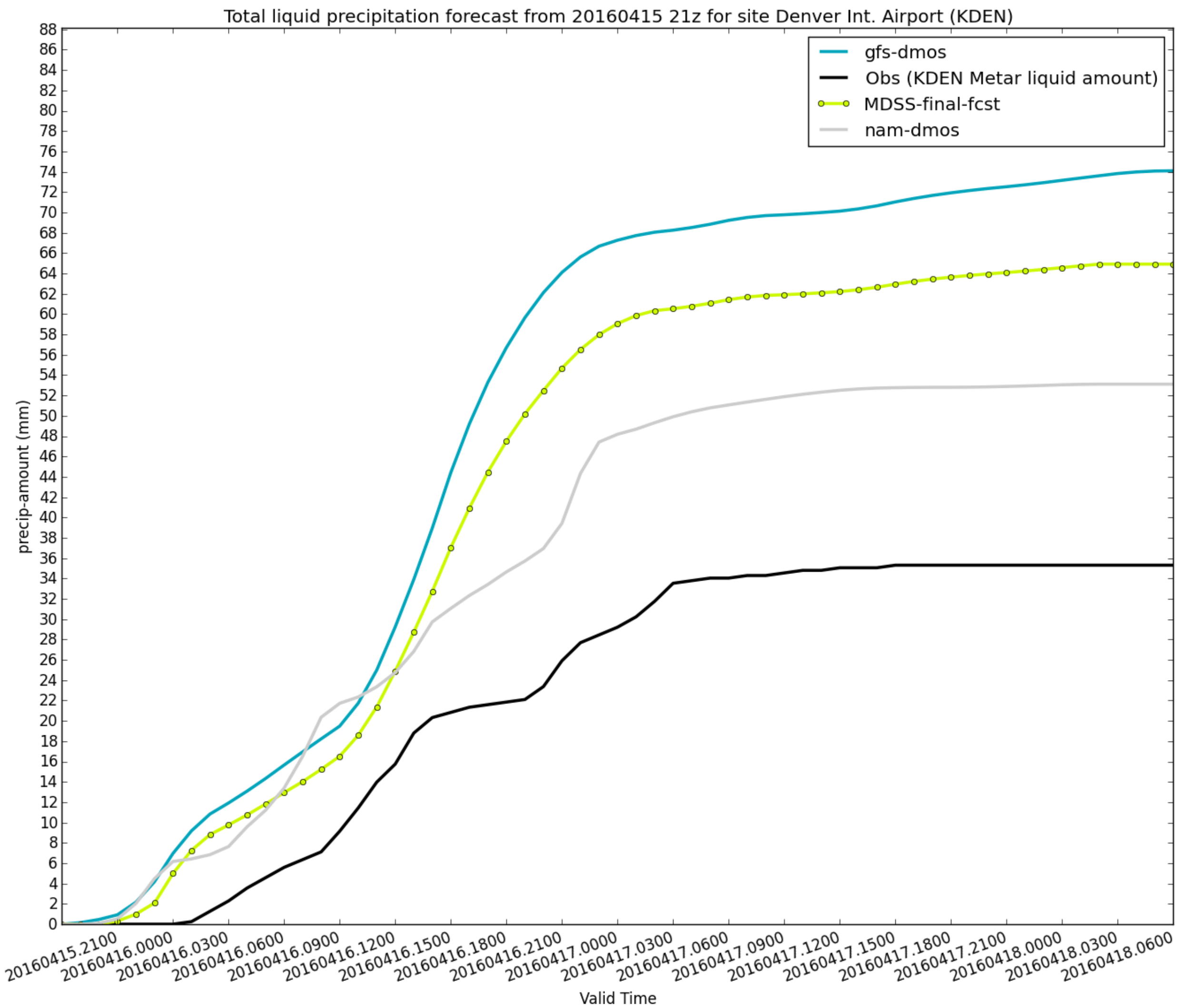

Figure 18: Total liquid precipitation forecast from 2pm (21z) on April 15, 2016

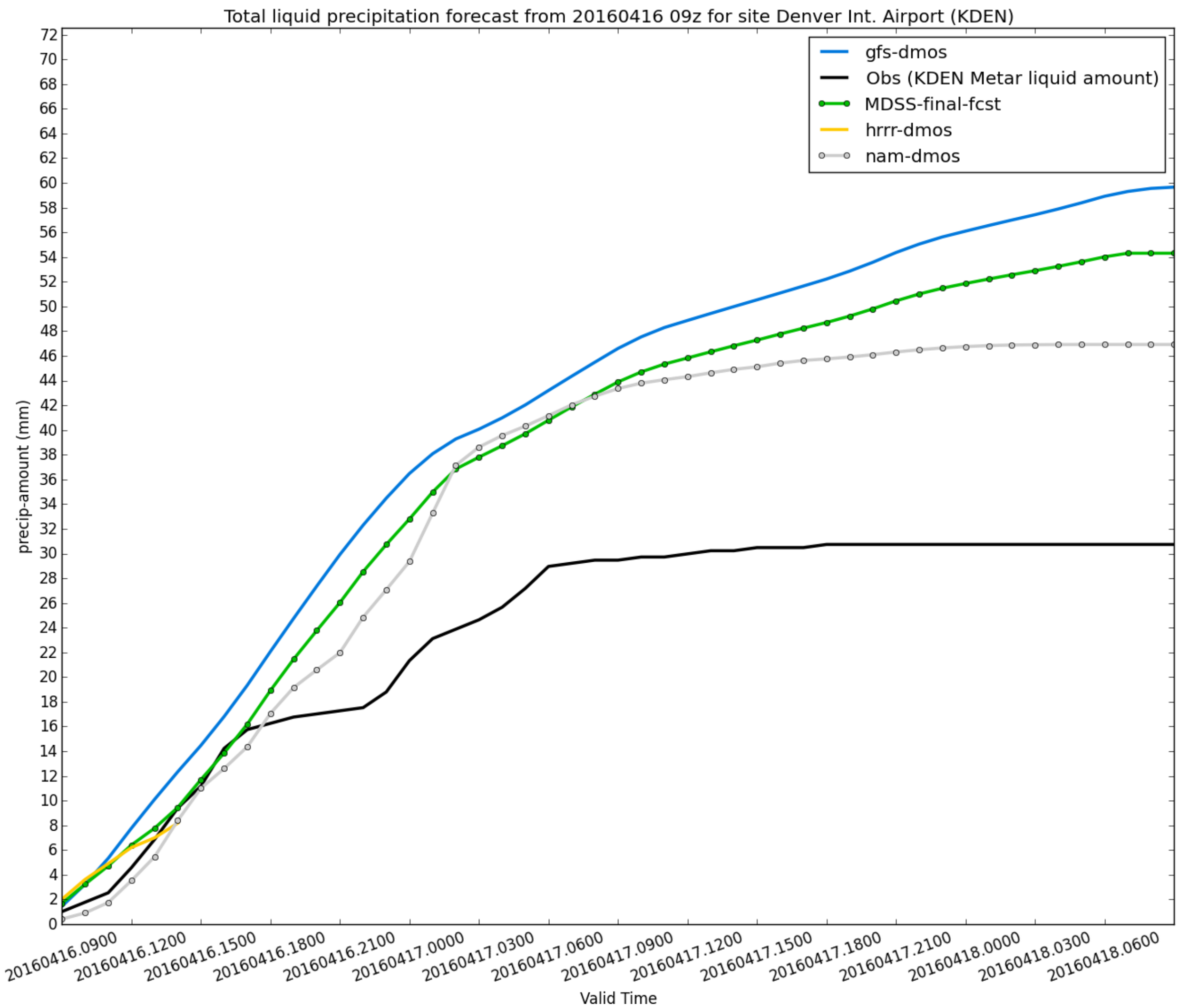

Figure 19: Total liquid precipitation forecast from 2am (09z) on April 16, 2016 to compare HRRR model

Summary and Future Recommendations

Overall MDSS shows good performance for most of the atmospheric state variables such as air temperature, dew point temperature, wind speed and cloud cover. A comparison of last year's MDSS performance to this year's shows some improvement for most of these variables. It should be noted that some of the core model components were updated or changed throughout the course of this last season and this likely contributed to some change in skill, although some of the differences can be attributed to different weather from one season to the next. In December one of the core models in MDSS, GFS was upgraded with better spatial and vertical resolution as well as some better physics. The new GFS data was automatically used by the DIA MDSS system starting in late December. In late February the system was configured to use the new high-resolution HRRR model data. The RAP model was replaced with the HRRR model in the MDSS forecast engine and was given significant weight for the precipitation forecast based on some error statistics (ETS). Initially the system was configured to use the first 6 hours of the HRRR but late in the season the system was modified to use up to 12 hours from the HRRR. Finally, a new global model, the GEM was added to the MDSS system in early April. Since the GEM was included so late in the winter season, its forecast performance and influence in MDSS will be examined for next year's verification report. New to this year's verification report was the inclusion of precipitation statistics (ETS scores). This was an important exercise both during the season and after the season to see what models perform the best for predicting precipitation and snowfall. The results of the verification helped setup new static model weights for the MDSS precipitation forecast. The ETS stats plots and forecast total precipitation plots from the case studies show the positive results from the new static weights and the inclusion of the HRRR in the precipitation forecast (during the spring events). Looking at the case studies, generally MDSS does quite well predicting the total precipitation amounts but clearly has some issue related to converting liquid to snowfall and properly predicting the correct total snowfall amount. The issue is likely a combination of having the wrong precipitation type at the beginning of an event (indicating more rain than snow) and also, more importantly using too low of a snow ratio during the course of an event. This issue is most evident during relative warm spring snow storms. Work will be done during the upcoming season to improve the snow ratio and the overall MDSS snowfall forecast. Additional work will be done to see if the GEM model can be used in the precipitation forecast.