Denver International Airport MDSS Demonstration Verification Report for the 2014-2015 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. This is the annual verification report for the DIA MDSS Research and Development Project for the 2014-2015 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 snowfall forecast and how the human-in-the-loop, i.e. Weathernet influenced the forecast guidance for each case. Summaries are given after each section.

Forecast Error Statistics

This section will look at MDSS forecast error statistics over the 2014-2015 winter season. Plots of RMSE (root mean square error) and Bias are examined for air-temperature (T), dewpoint-temperature (dewpt), wind-speed, and pavement-temperature (road-T). The statistics are based on all 15z (8am MST, 9am MDT) forecasts generated from November 1, 2014 to April 30, 2015. On 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) are based on forecasts for all Colorado Plains sites: 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 4 primary DIA runway sites, plus the Pena Blvd road site. The road-T statistics were calculated using the recommend road-T forecast. Error characteristics are examined for each variable and recommendations are made about improving forecast error / reducing bias.

Air-Temperature (T) statistics.

The RMSE plot (figure 1) for T shows that the MDSS-final-fcst is better on average than any one of the model components and has average errors of around 2.5 degs C at 24 hours out. The plots also shows how forward-error-correcting the forecast greatly reduces the forecast error in the first three hours of the forecast. The Bias plot (figure 2) shows that the MDSS-final-fcst has lower bias on average than any single model component. In general the final-fcst has a slight cold-bias across most lead-times, and this is more noticeable during morning and middle of day. Overall the MDSS T forecast shows good skill.

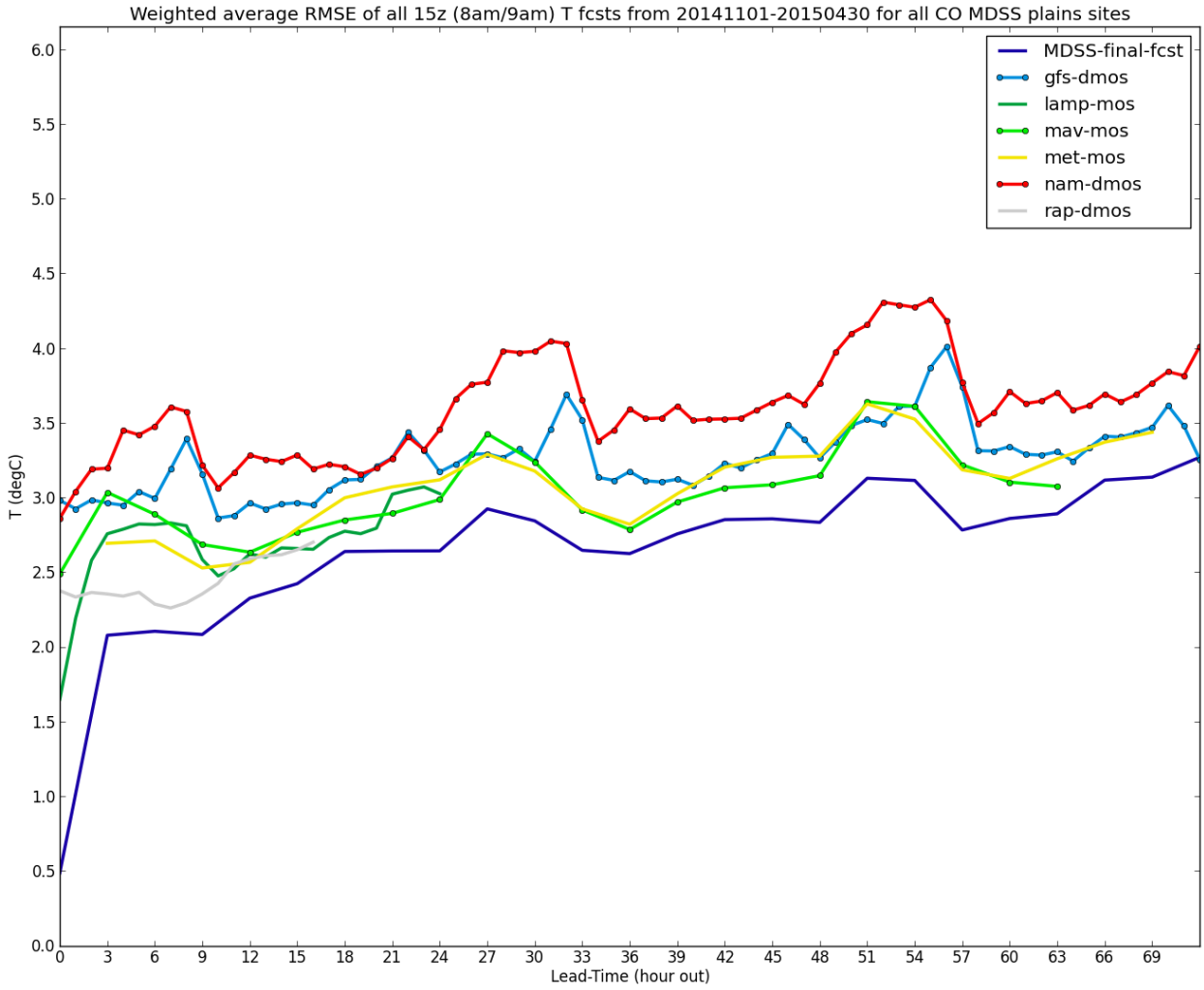

Figure 1: RMSE of air-temperature (T) forecast

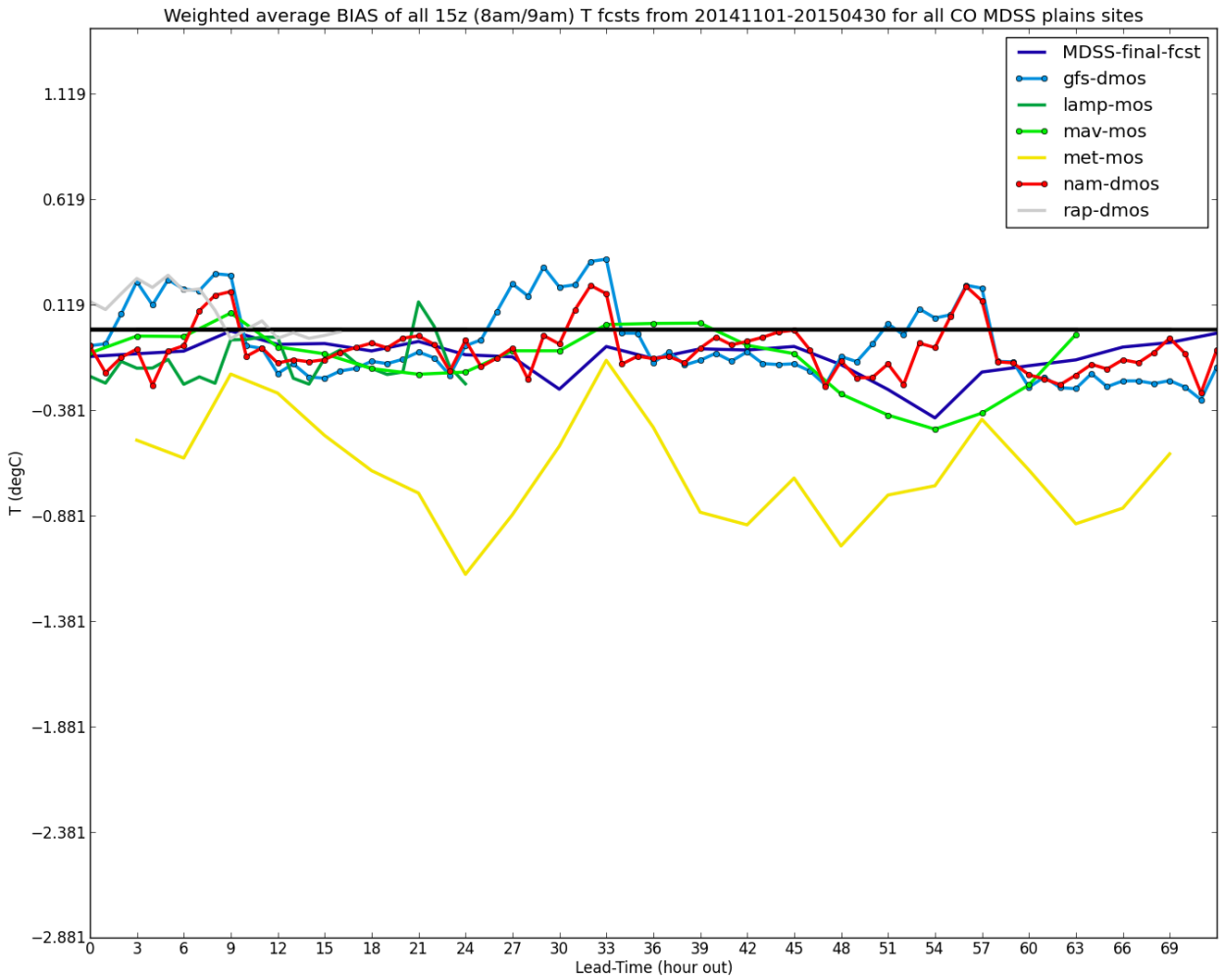

Figure 2: Bias of air-temperature (T) forecast

Dewpoint-Temperature (dewpt) statistics

The RMSE plot (figure 3) for dewpt shows that the MDSS-final-fcst is better on average than any single model component and has an average error of around 2.2 degs C at 24 hours out. The plot also shows the impact of forward-error-correction, by reducing the final-fcst dewpoint error in the first 3-6 hours of the forecast. Certain model components such as the NAM and GFS show much higher dewpoint errors during the middle of the day. The Bias plot (figure 4) shows that the MDSS-final-fcst has lower bias on average than any single model component. In general the final-fcst has little average bias across most lead-times. The bias plot also shows that the GFS and especially the NAM over-forecast dewpoints during the middle of the day and this contributes to the higher errors on the RMSE plot. Overall the MDSS dewpt forecast shows good skill.

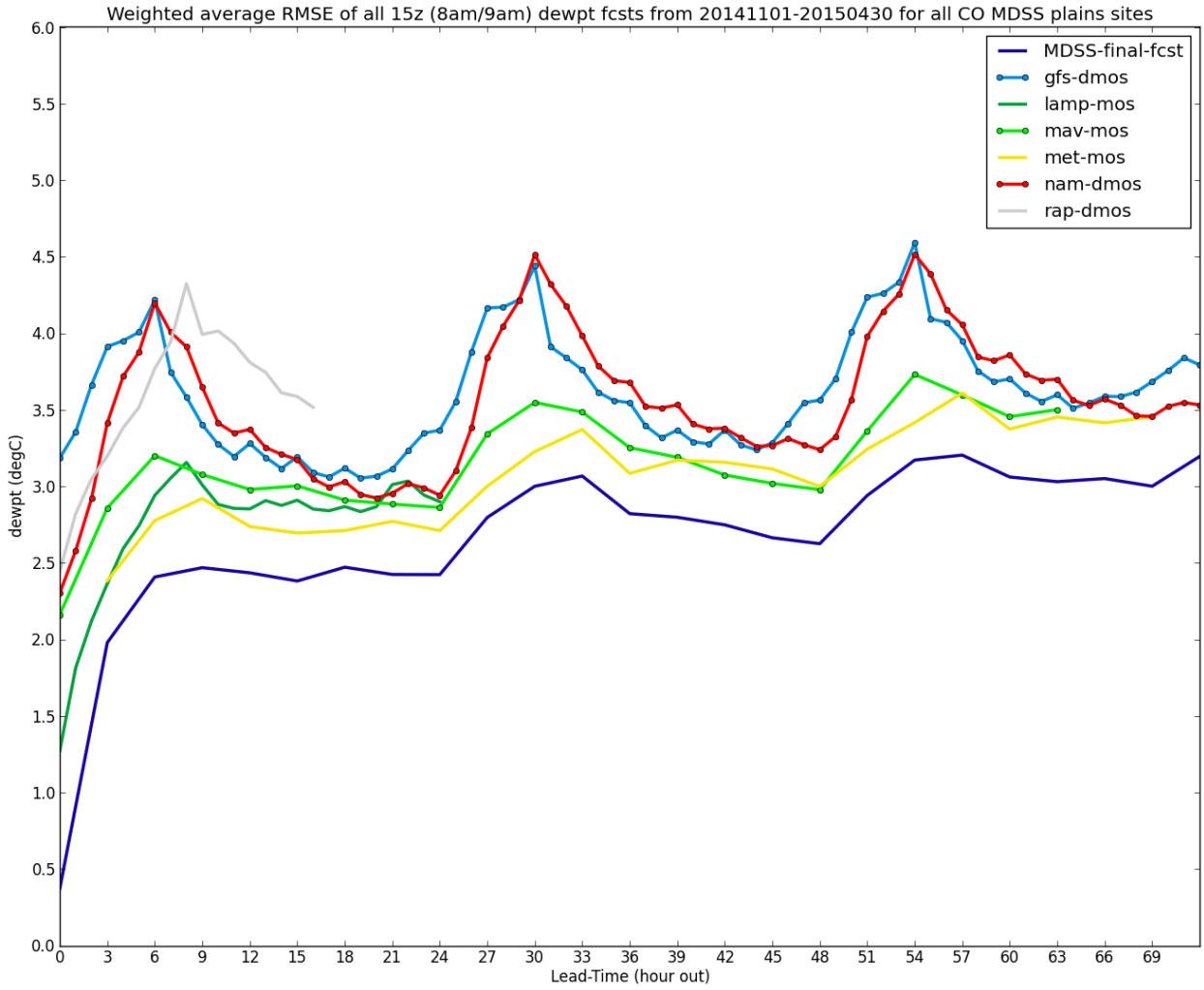

Figure 3: RMSE of dewpoint-temperature (dewpt) forecast

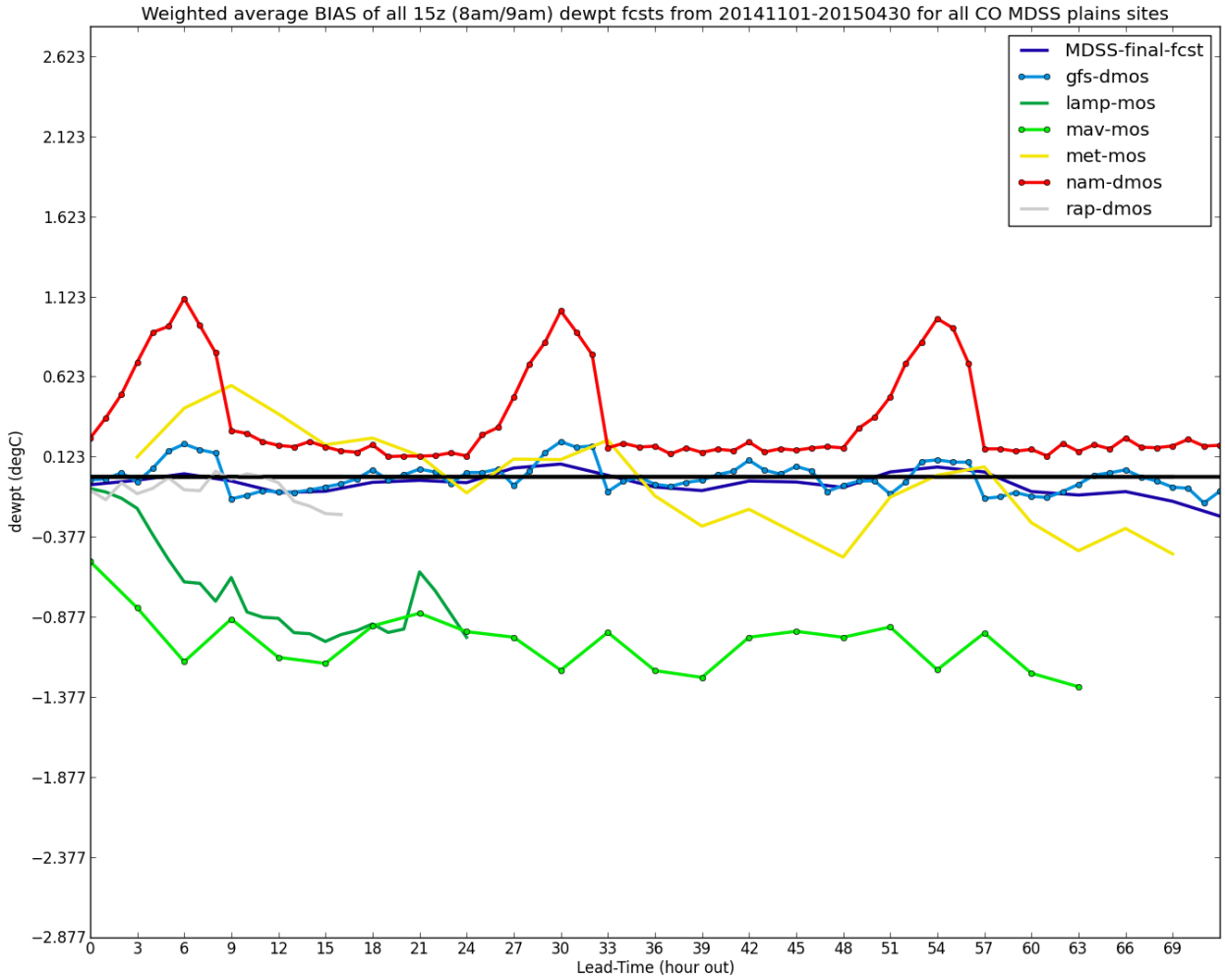

Figure 4: Bias of dewpoint temperature (dewpt) forecast

Wind-speed statistics.

The RMSE plot (figure 5) for wind-speed shows that the MDSS-final-fcst is better on average than any single model component and has an average error of around 1.8 m/s at 24 hours out. Since there is not as much spread in the model forecast skill for wind-speed compared to the other variables, the MDSS-forecast errors are closer to the model component errors. Forward-error correction reduces the error in the first three hours. The Bias plot (figure 6) shows that the MDSS-final-fcst doesn't have much bias across most lead-times but does show a slight positive bias (over forecast of wind-speed) in the afternoon hours. This can be attributed to the fact that all three MOS forecast modules (LAMP, MET MAV) over-forecast the wind-speed in the afternoon. Overall the MDSS wind-speed forecast shows good skill.

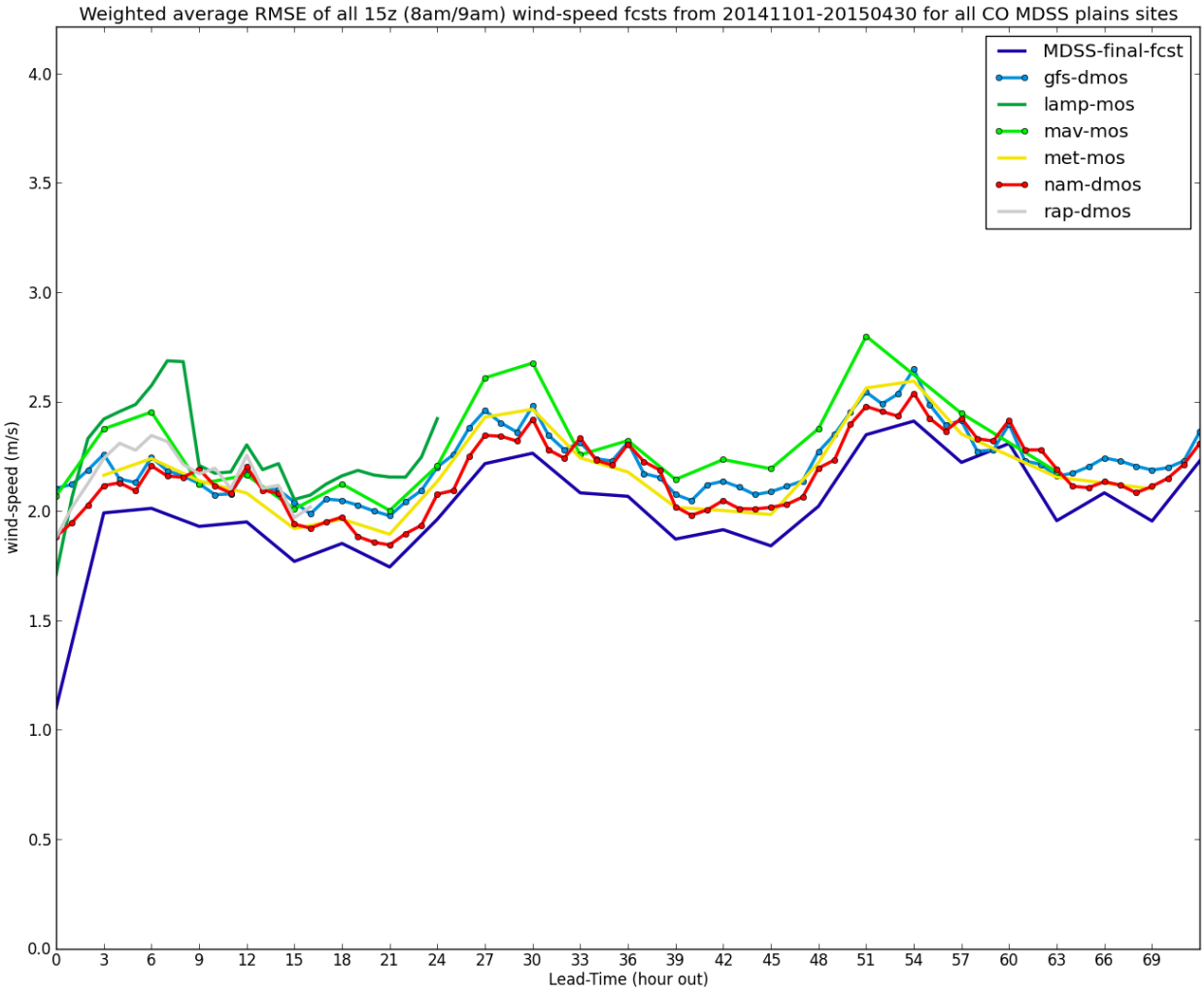

Figure 5: RMSE of wind-speed forecast

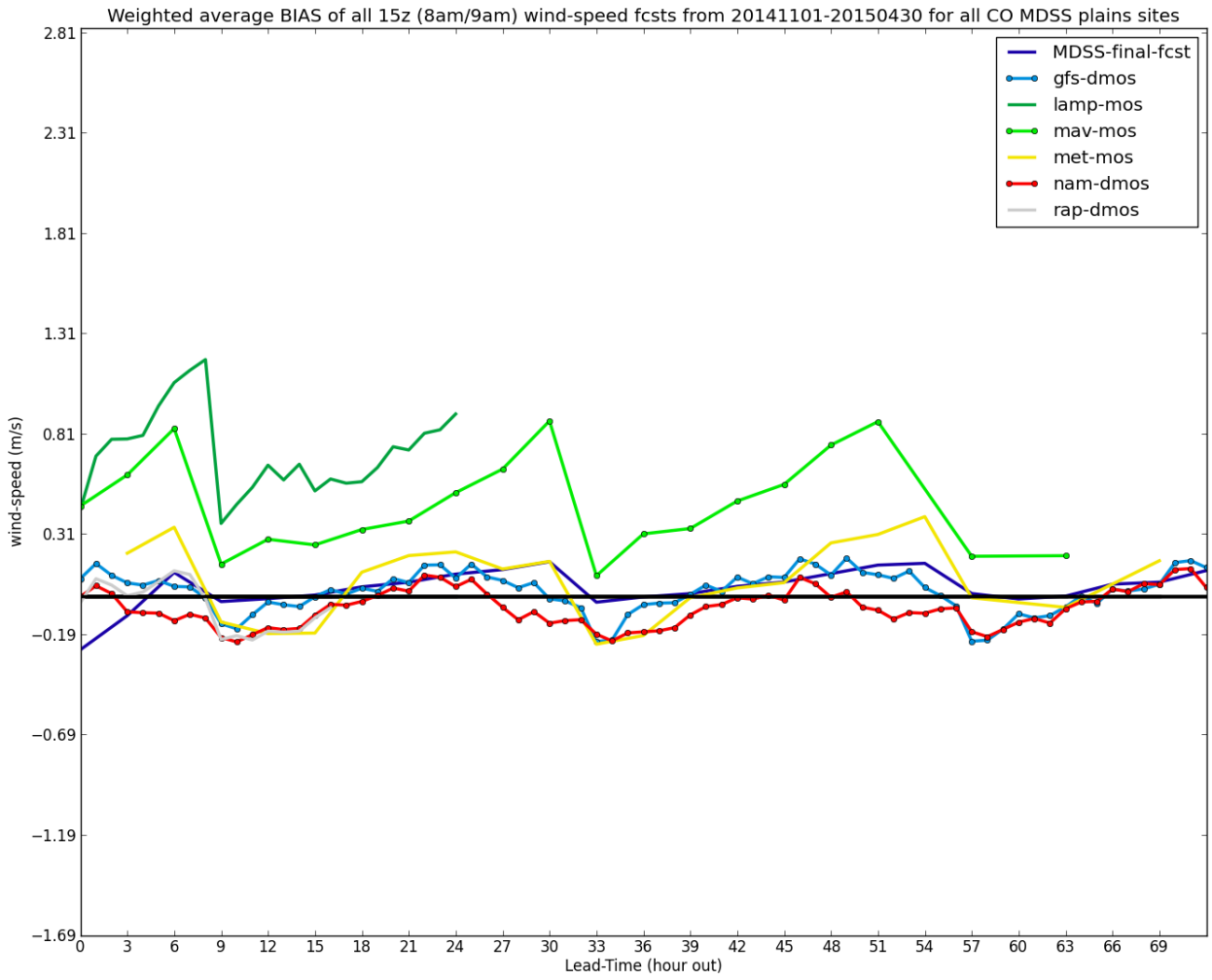

Figure 6: Bias of wind-speed forecast

Pavement-Temperature (road-T) statistics.

The RMSE plot (figure 7) for road-T shows a strong diurnal pattern in the forecast errors. 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 4-5 deg C. The forecast errors are considerably less during the evening, overnight and morning hours, with an average error of 2 degC during those times Looking at the Bias plot (figure 8) it's obvious that the large errors during the afternoon can be attributed to a cold-bias in the road-T forecast in the afternoon. Overall the MDSS road-T forecast seems to perform decent during precipitation events (based on the analysis of the case studies below), but shows less skill predicting road-T during non-storm conditions and during the shoulder seasons (fall and winter).

The pavement model METRO, used in MDSS, has been known to produce warm biases during the fall and spring. Research was done to alleviate this problem by using air-T observations, if no actual road-T observations exist, to initialize the pavement model. Using air-T observations may be creating a cold-bias in the road-T forecast during the day. Research will be done during the next contract (years 2016-2018) to examine how best to initialize METRO when no actual road-T observations exist.

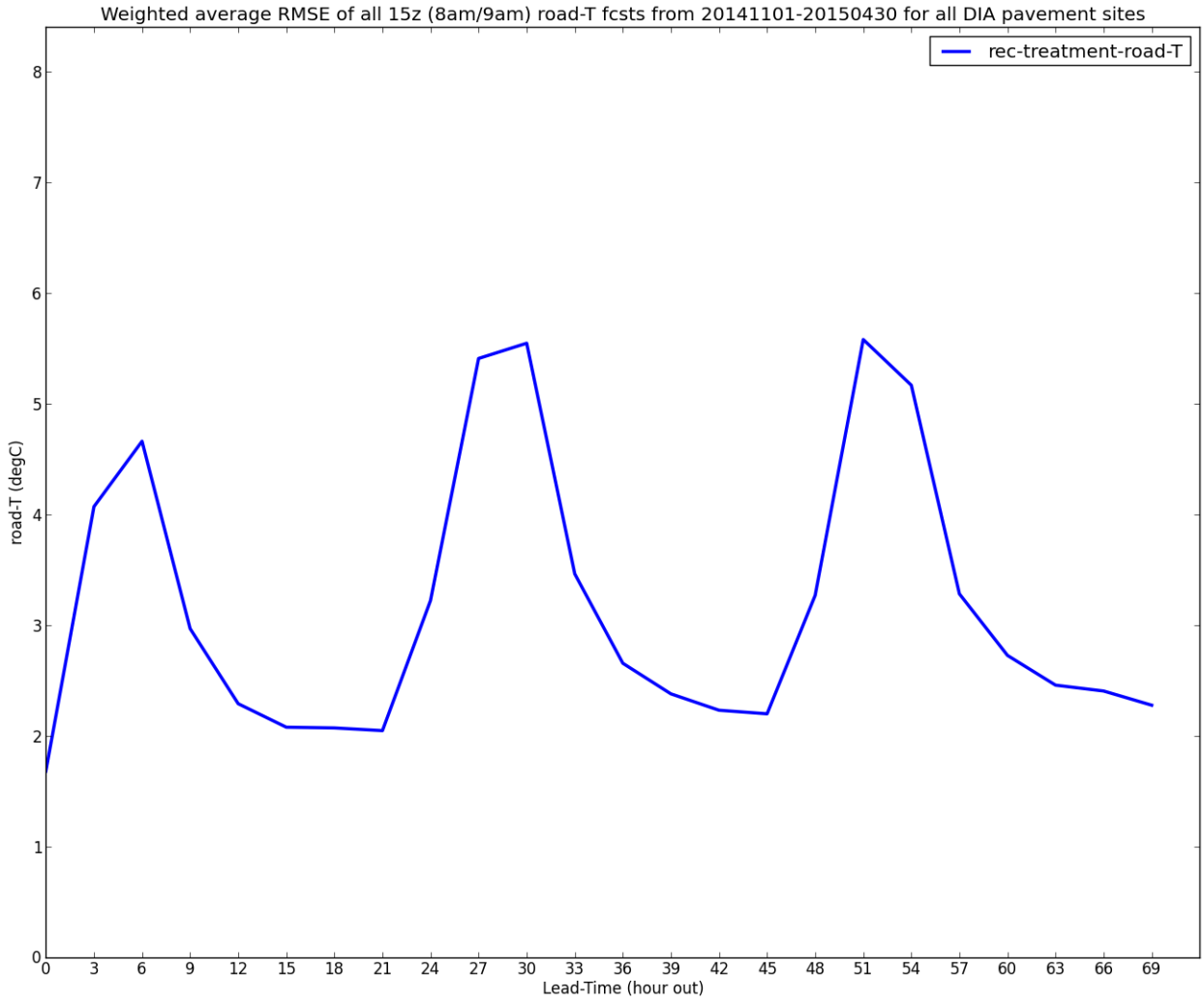

Figure 7: RMSE of pavement-temperature (road-T) forecast

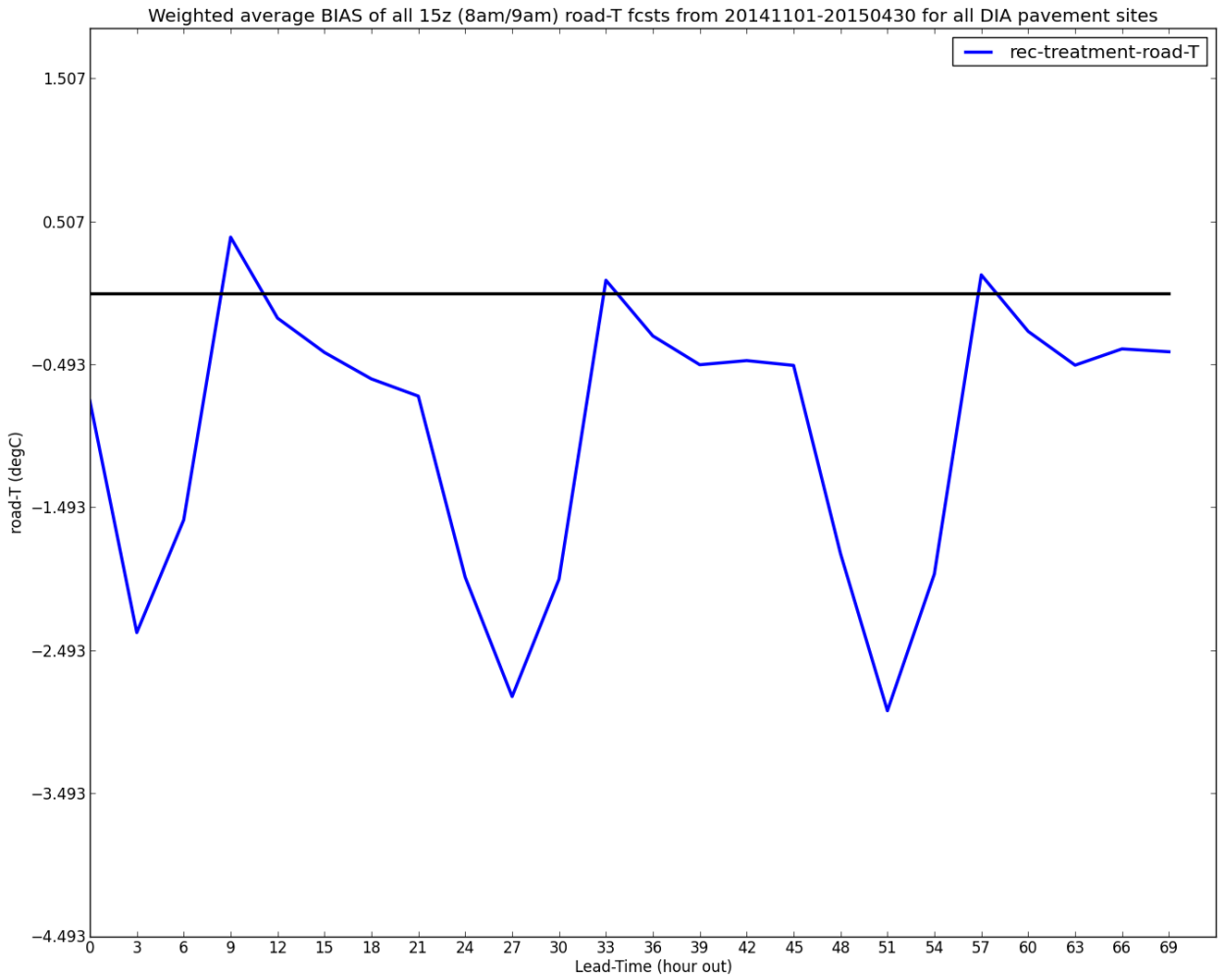

Figure 8: Bias of pavement-temperature (road-T) forecast

Statistics Summary

Overall MDSS shows good forecast skill for air-temperature, dewpoint-temperature and wind-speed. For all of these variables the MDSS forecast is better, on average than any single model component. In general, the MDSS weather forecast for these variables show slightly higher errors during the middle of the day / afternoon, and this seems to be the most challenging time to forecast. The MDSS pavement-temperature forecasts could be improved. The road-T stats show good skill during the evening, overnight and early morning, but have much higher errors during the middle of the day and into the afternoon (during peak heating). Research will be done to see if different pavement model initialization techniques could improve the MDSS road-T forecast during the afternoon hours. Future verification reports will compare future season's statistics to this season's statistics.

Storm Event Case Studies

This section will look at some storm event case studies and highlight some unique aspects specific to each case.. One focus of this section will be on the human in the loop influence on the forecast, i.e. Weathernet's forecast guidance and how it compared to MDSS and observations. Other aspects of this analysis include pavement temperature forecasts that may be too warm and also a case that looks at the MDSS snow ratio and how it impacts the total snowfall forecast. For each case, the MDSS forecast event summary is shown for the runway site 16L/34R (DIA01), along with a table that shows total snowfall forecast from MDSS, total snow forecast from Weathernet and the observed total snowfall recorded at DIA as listed as the official snow total for KDEN (from the Denver/Boulder National Weather Service climate page). Some of the cases include a plot that compares the forecast pavement-temperature (road-T) for runway site 16L/34R (DIA01) to the actual observations as recorded by the RWIS puck embedded in that runway. Note that local times (MST or MDT) are used in the case descriptions but the time-series plots use UTC. 16z corresponds to 9am MST and 15z corresponds to 9am MDT.

Case: November 11-12, 2014. Cold, light snow event.

This event was characterized by an unseasonable cold arctic air-mass and prolonged light snow event. Forecasts issued about 12-24 hours before the main snow event are examined for this case. The November 11th, 9am MDSS forecast had very light snow amounts and only forecast total snowfall of 0.40" at DIA by Wednesday night. Weathernet's forecast issued at 9am on the 11th mentions that MDSS is likely too low on snow amounts and calls for 2 to 3.5 inches of snow by Wednesday night. The airport officially picked up 2.3 inches of snow.

For this case the MDSS forecast was considerably low on snow amounts and this was because MDSS quality controls (qc's) out very low precipitation amounts before converting to snow. This was a cold-event with very light precipitation but the snow still accumulated effectively because it was so cold. Since MDSS removed many hours of very light precipitation, the total snowfall forecast of 0.6 inches was well below the observed amount of 2.3 inches. The Weathernet forecast recognized the low amounts coming from MDSS and called for amounts of (2-3.5 inches) which was much more inline with what fell at DIA. Weathernet's guidance improved the snow forecast in this case.

November 11-12, 2014	
MDSS Snow Total Forecast	**0.6"**
WeatherNet Snow Total Forecast	**2 to 3.5"**
Observation (measured at DIA)	**2.3"**

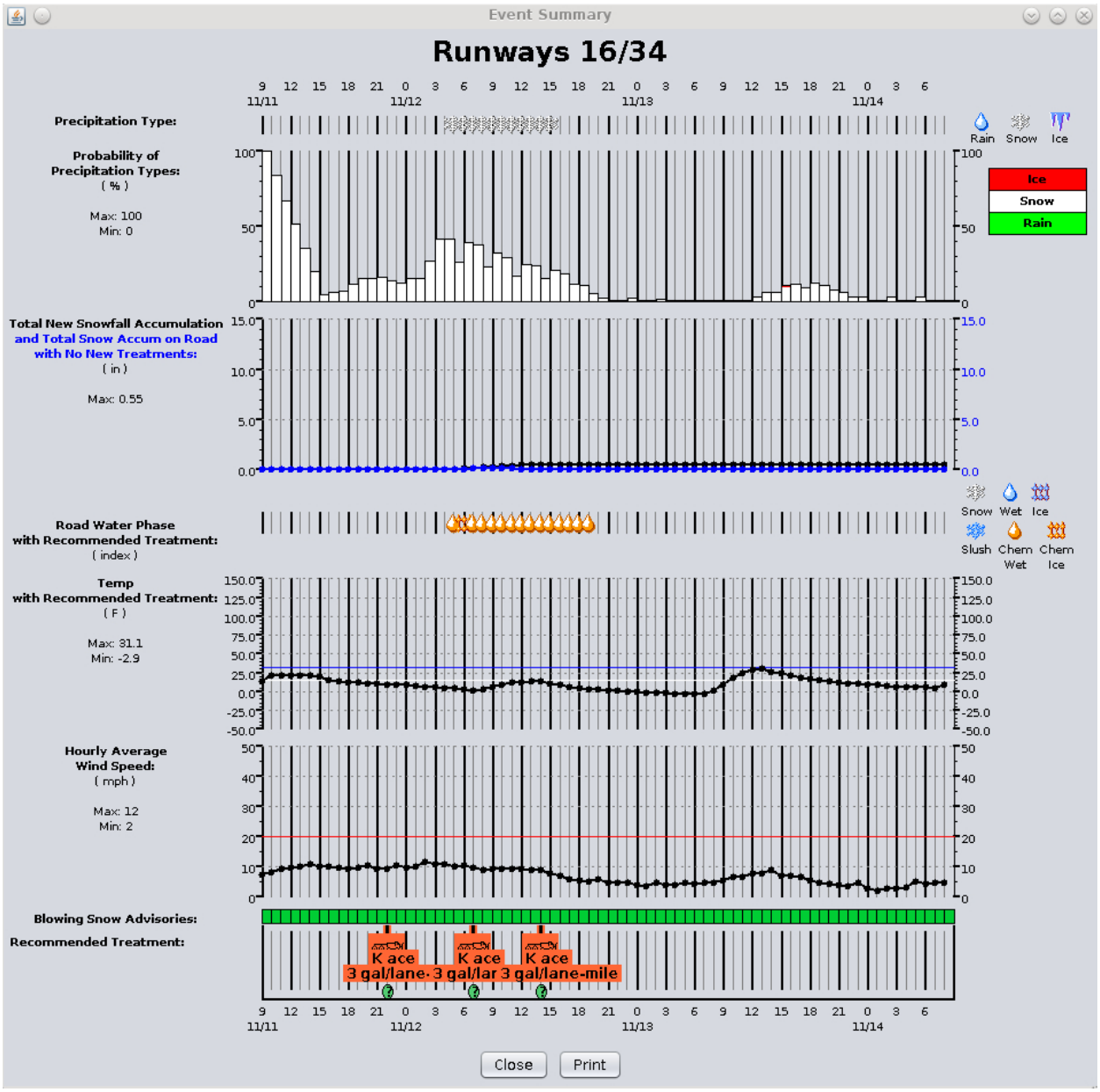

Figure 9: MDSS event summary forecast starting at 9am on November 11, 2014

Case: February 3-4, 2015. Warm, light snow event.

This event was characterized by a band of snow that moved through during the morning of February 4th. Air-temperatures were forecast to be in the low to mid 30s during the day so fairly warm for a snow event. Forecasts issued 24 hours before the snow event are examined for this case. The February 3rd, 9am MDSS forecast showed only 0.6 inches of total accumulation at DIA. Weathernet's forecast issued at 9am on the 3rd called for 1 to 3 inches of snow. The airport officially picked up 1 inch of snow on February 4th.

For this case the MDSS forecast was too low on snow amounts because the snow-ratio it uses to convert liquid precipitation to snow was too low in the mid-morning hours on the 4th. Comparing the liquid precipitation rate values to the snow rate values, MDSS was using a snow-ratio of less than 5:1 during the mid-morning hours. Typically during winter on the Front-range we have snow-ratios between about 11:1 and 15:1, so 5:1 is very low for February. Comparing the forecast liquid precipitation to the observed snowfall at DIA (of 1 inch), if the snow-ratio would have been closer to about 14:1, MDSS would have correctly forecast the snow amounts of around 1 inch. The snow ratio is calculated from air-temperature and some other forecast variables. This case highlights the fact that sometimes the snow-ratio calculation can be way off compared to reality. The snow-ratio algorithm could be improved in the future to come up with more accurate snow-ratios. The Weathernet forecast called for 1-3 inches of snow which was closer to the observed amount of 1 inch. MDSS did well with the timing of snowfall but did not do well forecasting total snowfall amounts. Weathernet's guidance helped the forecast in this case.

February 3-4, 2015	
MDSS Snow Total Forecast	**0.6"**
WeatherNet Snow Total Forecast	**1 to 3"**
Observation (measured at DIA)	**1"**

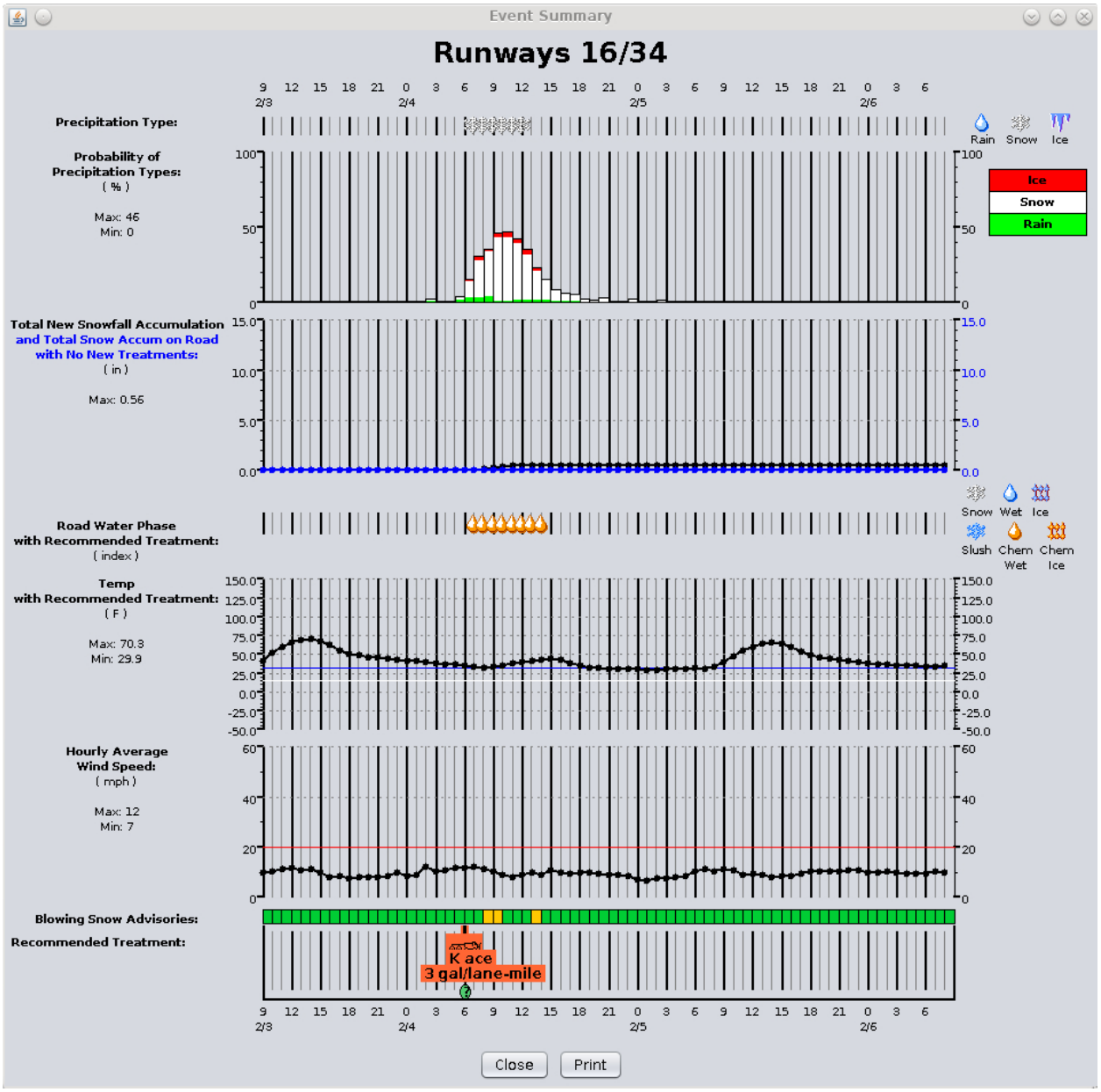

Figure 10: MDSS event summary forecast starting at 9am on February 3, 2015

Case: February 15-16, 2015. Moderate snow event with pavement temps falling below freezing during the evening.

This event was characterized by a moderate snow event with some banded snow initially on the evening on February 15th and then some light to moderate snow during the day on the 16th. Forecasts issued about 12-24 hours before the event are examined for this case. The February 15th, 9am MDSS forecast had 4.2 inches of snow total for DIA. Weathernet's forecast issued at 9am on 15th called for 2.5 to 3.5 inches of snow. The Weathernet forecast also mentioned that

they thought MDSS was too warm with pavement temperatures during the afternoon on the 15th when snow was expected to start. The airport officially picked up 4.8 inches of snow.

The plot below (Figure 12), shows the MDSS forecast pavement temperatures compared to the observed pavement temperatures for runway 16L/34R. Weathernet had indicated that the pavement temp would fall below freezing as early as 5pm on the 15th but the observed runway temperature did not actually fall below freezing during the 15th . It was close to freezing (< 1 degC) by 8pm on the 15th and remained near 1 degC through the night. In this case the MDSS forecast accurately predicted when the pavement temperature would get below 1 deg C and was closer to the observed pavement temperatures than what was indicated by Weathernet. Overall MDSS had a good handle on this event and it's forecast of 4.2 inches of snow was very close to the observed amount of 4.8 inches. Weathernet's guidance did not improve the forecast for this case.

February 15-16, 2015	
MDSS Snow Total Forecast	**4.2"**
WeatherNet Snow Total Forecast	**2.5 to 3.5"**
Observation (measured at DIA)	**4.8"**

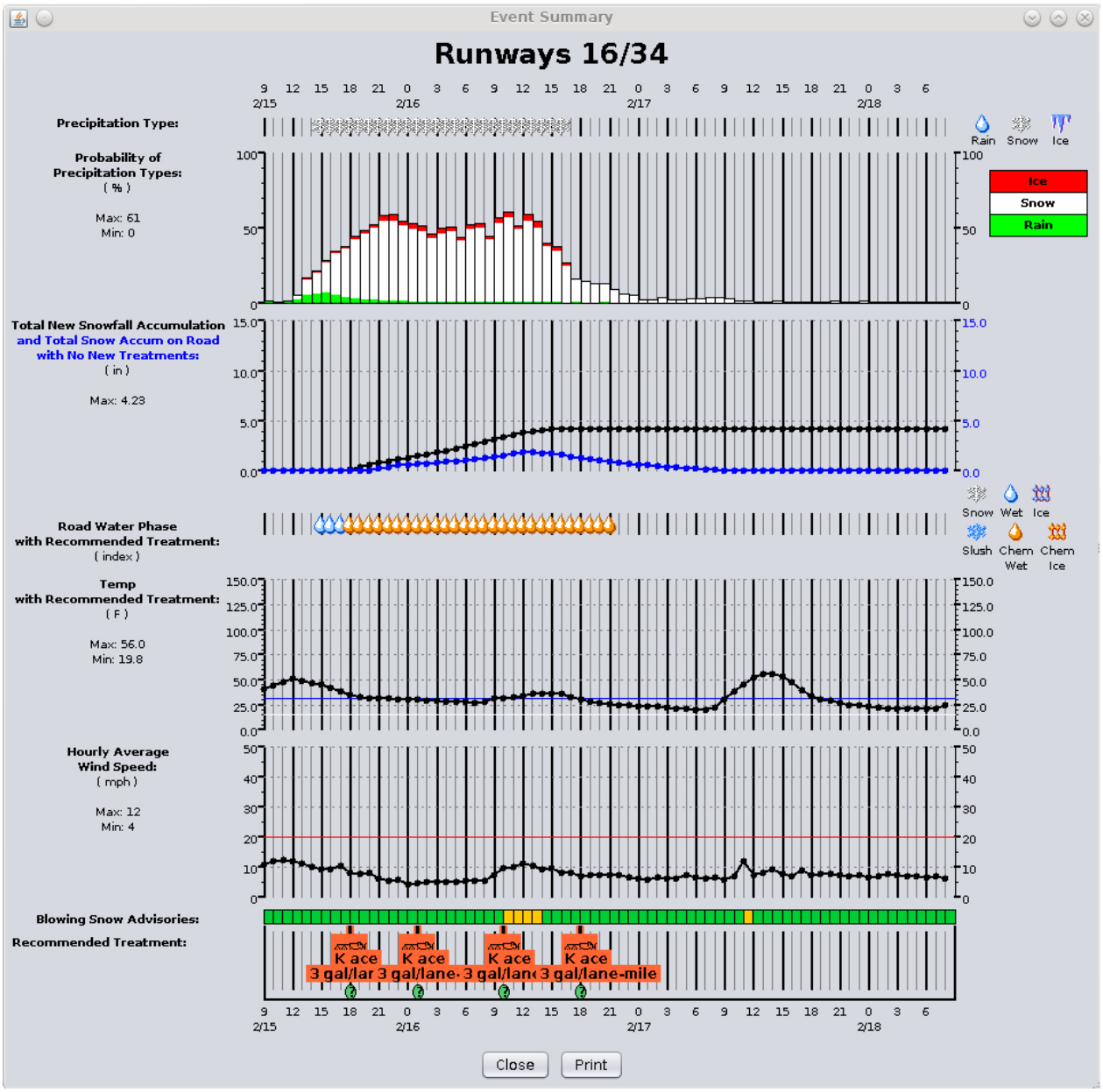

Figure 11: MDSS event summary forecast starting at 9am on February 15, 2015

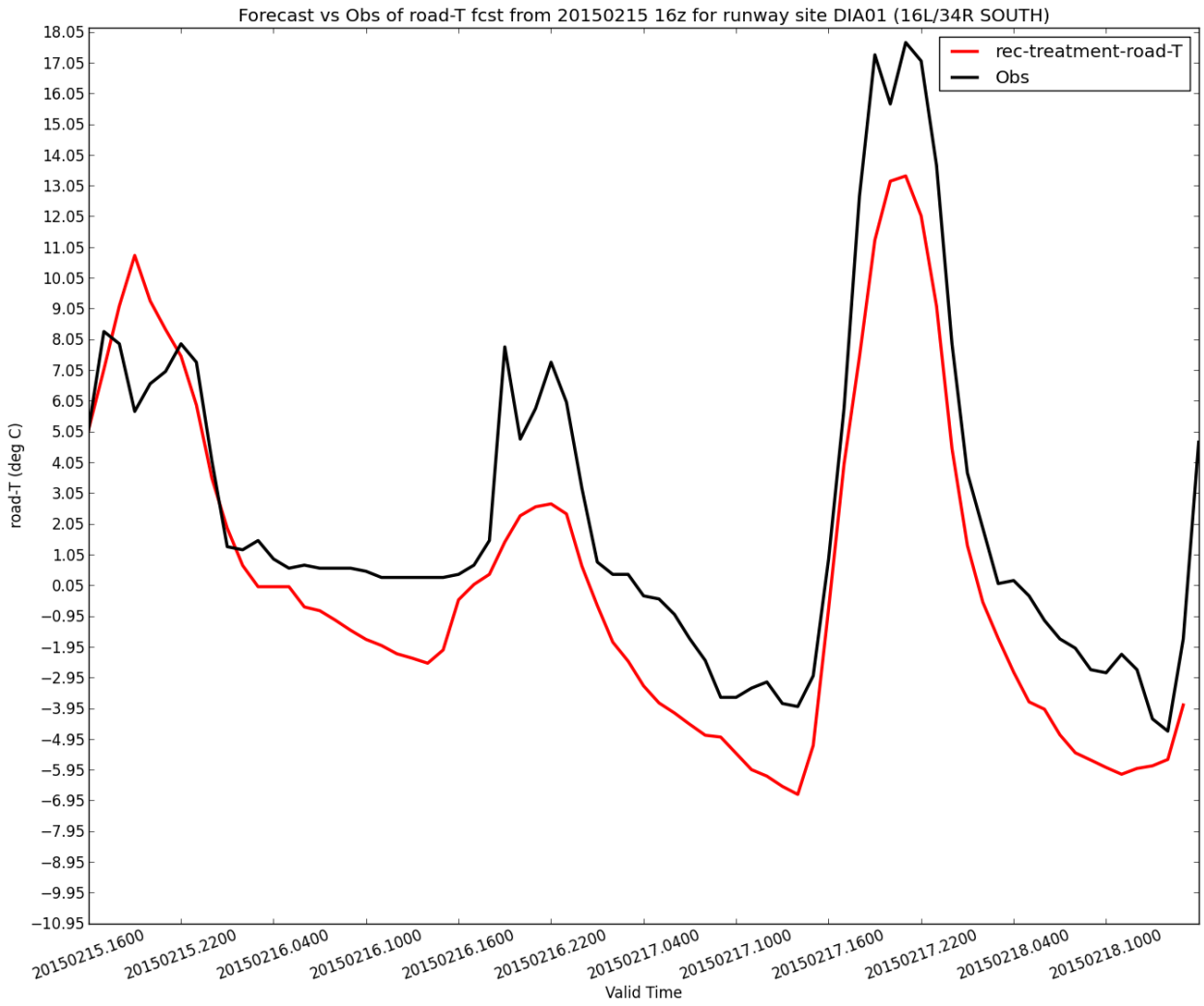

Figure 12: MDSS road-T forecast vs. observations for runway 16L/34R . Forecast generated at 9am on February 15, 2015

Case: February 20-22, 2015. Moderate, prolonged snow event that came in two waves.

This event was the largest snow-storm of the season for DIA and was characterized by periods of moderate to heavy snow that came in two waves, one on the evening of the 20th and the other during the evening of the 21st into the morning of the 22nd. The February 20th, 9am MDSS called for 9 inches of snow at DIA by the evening of the 22nd. Weathernet's forecast issued at 9am on the 20th called for 11 to 15 inches of snow. The airport officially picked up 10.5 inches of snow total.

This event was well forecast by both MDSS and Weathernet. MDSS indicated that most of the snow would fall during the evening of the 21st into the morning on the 22nd and that is when most of the snow fell at DIA. Both Weathernet and MDSS indicated snow would continue into Sunday evening whereas in reality most of the snow ended on Sunday afternoon.

Weathernet indicated that they felt MDSS was too warm with pavement temps on Saturday afternoon / evening and that subsequently the pavement snow forecast was too low on snow amounts during that time period. The plot below (Figure 14), shows the MDSS forecast pavement temperatures compared to the observed pavement temperatures for runway 16L/34R. Observed runway temps fell to near freezing between 4pm-5pm and then held steady overnight. The MDSS forecast indicated temps falling below freezing between 6-7pm and then even colder pavement temps overnight. In this case, Weathernet did help improve the timing of freezing pavement temps on Saturday evening (the 21st) but both MDSS and Weathernet indicated pavement temps overnight that were colder than what was observed, and this was likely due to snow insulating the runway till the early morning hours. Overall the MDSS had a good handle on this event and despite a complicated forecast was able to quite accurately predict the main periods of snowfall and the total snowfall amount at DIA. Weathernet's guidance for this event did help with pavement temps but overall didn't change the jist of the MDSS forecast.

February 20-22, 2015	
MDSS Snow Total Forecast	**9.0"**
WeatherNet Snow Total Forecast	**11 to 15"**
Observation (measured at DIA)	**10.5"**

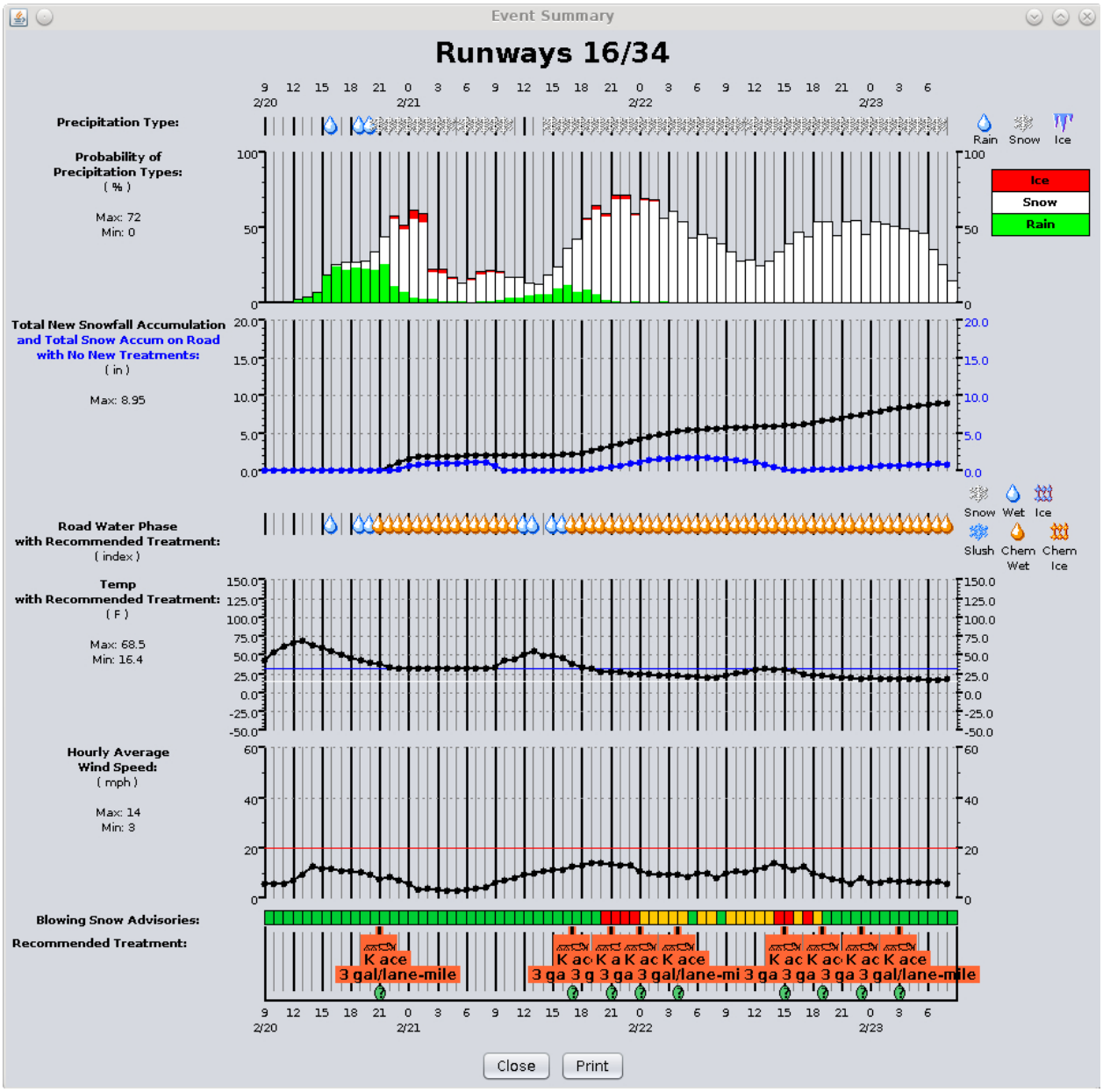

Figure 13: MDSS event summary forecast starting at 9am on February 20, 2015

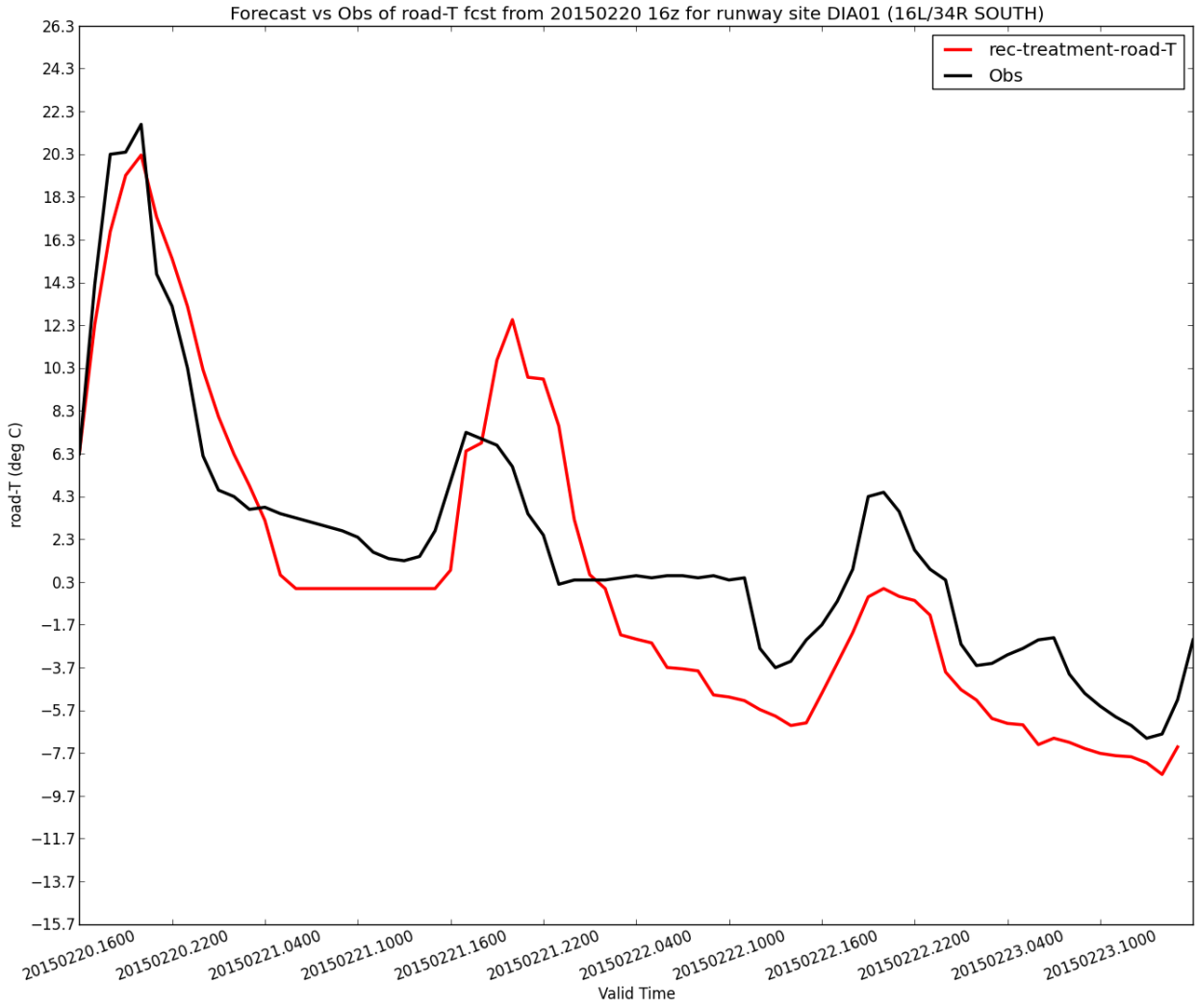

Figure 14: MDSS road-T forecast vs. observations for runway 16L/34R. Forecast generated at 9am on February 20, 2015

Case: April 1-3, 2015. Warm, light snow event. Rain changing to snow.

This event can be characterized as a warm, light snow event with rain initially changing over to snow. Forecasts issued about 24-36 hours before the snow event are examined for this case. The April 1st, 9am MDSS forecast called for rain switching to snow around 6pm on the 2nd and continuing overnight into the early morning on the 3rd. MDSS called for 2.6 inches of snow total at DIA. The Weathernet forecast issued at 9am on the 1st indicated snow primarily Thursday night (the 2nd) and called for 3-5 inches total at DIA by early on the 3rd. DIA officially recorded 1.2 inches of snow.

Weathernet indicated in their forecast that they thought MDSS was too low on snow amounts and also too warm with pavement temps on Thursday night (April 2nd). The plot below (Figure 16), compares the forecast pavement-temperature for runway site 16L/34R to the actual

observations. Even though MDSS was too warm with pavement temps during the afternoon and early evening on the 2nd it accurately predicted when the runway temps would fall below freezing during the early morning hours on the 3rd. Even though both MDSS and Weathernet called for more snow than actually fell, the MDSS forecast of 2.6 inches was closer to the observed snow total of 1.2 inches. Overall MDSS had a good handle on this event. Weathernet's guidance did help a little with pavement temperature recognition on Thursday night (the 2nd) but overall the MDSS had a more accurate snowfall forecast.

April 1-3, 2015	
MDSS Snow Total Forecast	**2.6"**
WeatherNet Snow Total Forecast	**3 to 5"**
Observation (measured at DIA)	**1.2"**

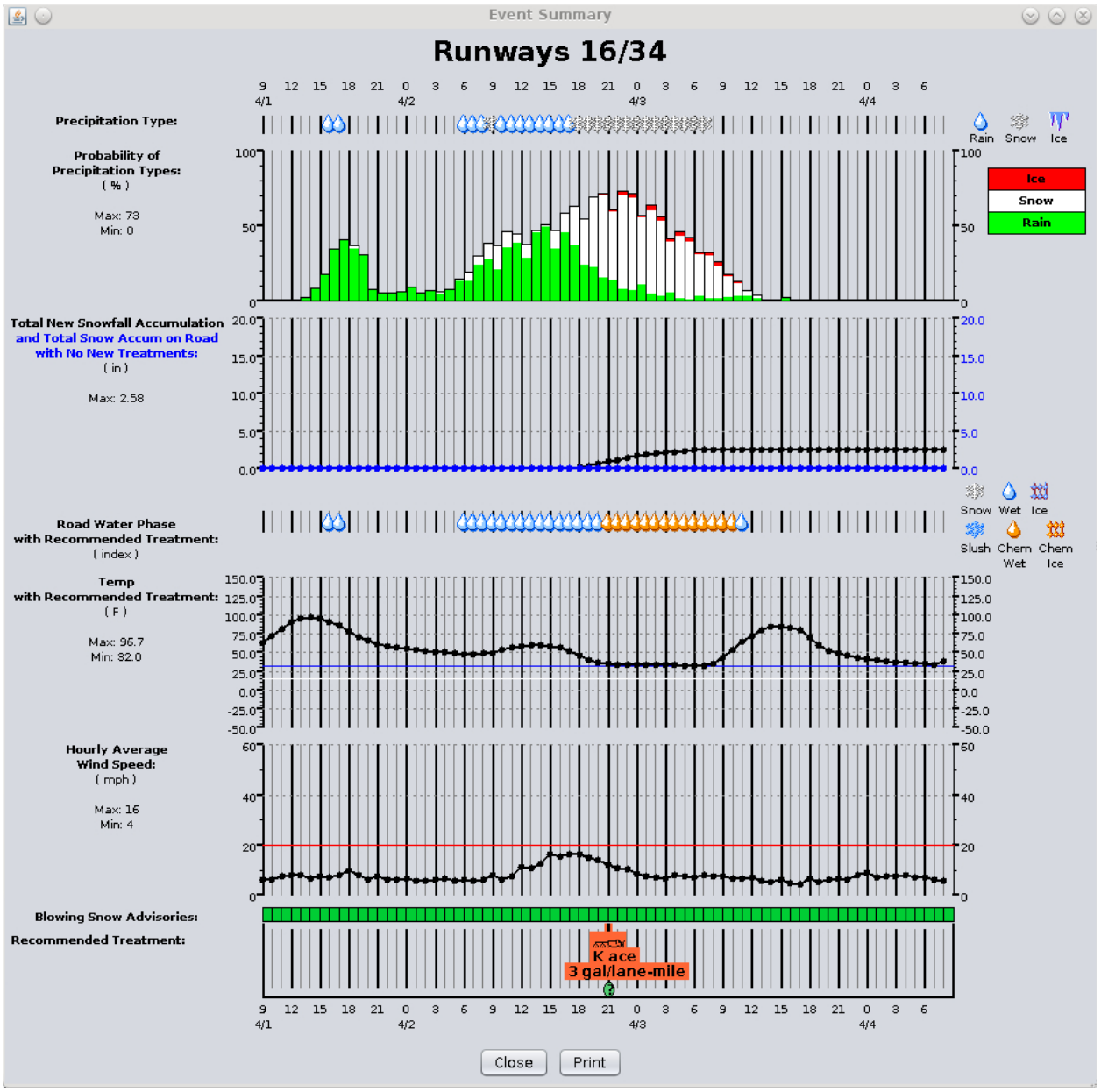

Figure 15: MDSS event summary forecast starting at 9am on April 1, 2015

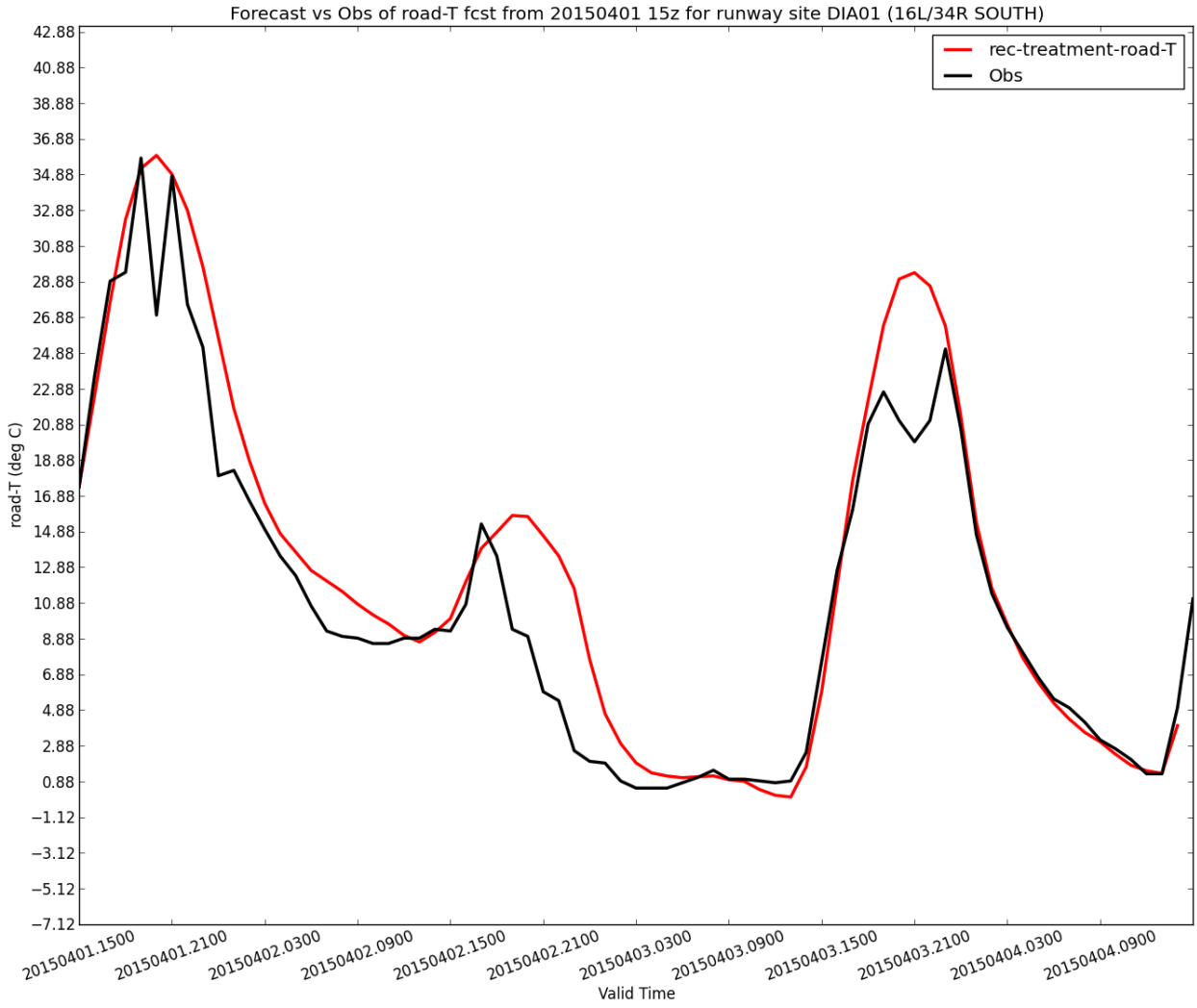

Figure 16: MDSS road-T forecast vs. observations for runway 16L/34R. Forecast generated at 9am on April 1, 2015

Case: January 1-2, 2015. Cold banded snow event. Heavy band of snow over DIA.

This event can be characterized by a small but intense snow event that occurred during a holiday, New Year's Day. DIA mentioned that this was a difficult event for them because the forecast originally called for light snow, with less than 1" of total accumulation. DIA ended up getting an intense band of snow that moved over the airport during the evening of January 1st that dropped ~2 inches of snow in just a few hours. DIA had only staffed for less than 1 inch of snow and being a holiday it was difficult to get additional staff out there and thus they were playing catch-up when the heavy snow started.

Forecasts issued about 6-9 hours before the snow event are examined for this case. The January 1st, 9am MDSS forecast called for light snow falling between about 4pm to 1am (January 1-2), with only 0.9 inches of total accumulation. The Weathernet forecast issued at 9am on January 1st mentioned off and on light snow falling from 10am to 4am (January 1-2) and called for only 0.2-0.9 inches total snowfall at DIA. The airport officially recorded 1.8 inches but DIA maintenance personnel mentioned it was significantly more than 1.8 inches over parts of the airport.

Although the timing of the snowfall was well forecast by MDSS, both Weathernet and MDSS missed the snowfall intensity and total snow amount. The plot below (Figure 18) compares liquid precipitation forecasts between the model components that went into the January 1st, 9am MDSS forecast to the final MDSS forecast. The observations are based on the liquid amounts recorded by the METAR site at Denver Int. Airport: KDEN. The plot also includes the qc'd MDSS forecast and the non-qc'd MDSS forecast. Looking at the plot it's clear that the reason the MDSS forecast was too low on snow intensity and amount was because both the GFS and especially the NAM were very low on snow rates and amounts. The MDSS forecast was helped out by the RAP in this case which did forecast the snow rates and amounts quite well during the morning of January 1st. The MDSS precipitation forecasts are based on a static, weighted combination of the RAP, NAM and GFS with 60% RAP, 25% NAM and 15% GFS. So the MDSS forecast was heavily influenced by the NAM and GFS which dragged the snow amounts down. Also, the plot shows the qc'd MDSS forecast versus the non-qc'd forecast because this was another case where a few hours of precipitation were qc'd out and in reality all of the precipitation fell as snow. Overall this was a mediocre forecast from the MDSS and Weathernet but considering the major models missed the event, MDSS was still closer than some of the input models. Future work will be done to optimize the model weights for better precipitation forecasts.

January 1-2, 2015	
MDSS Snow Total Forecast	**0.9"**
WeatherNet Snow Total Forecast	**0.2 to 1"**
Observation (measured at DIA)	**1.8"+**

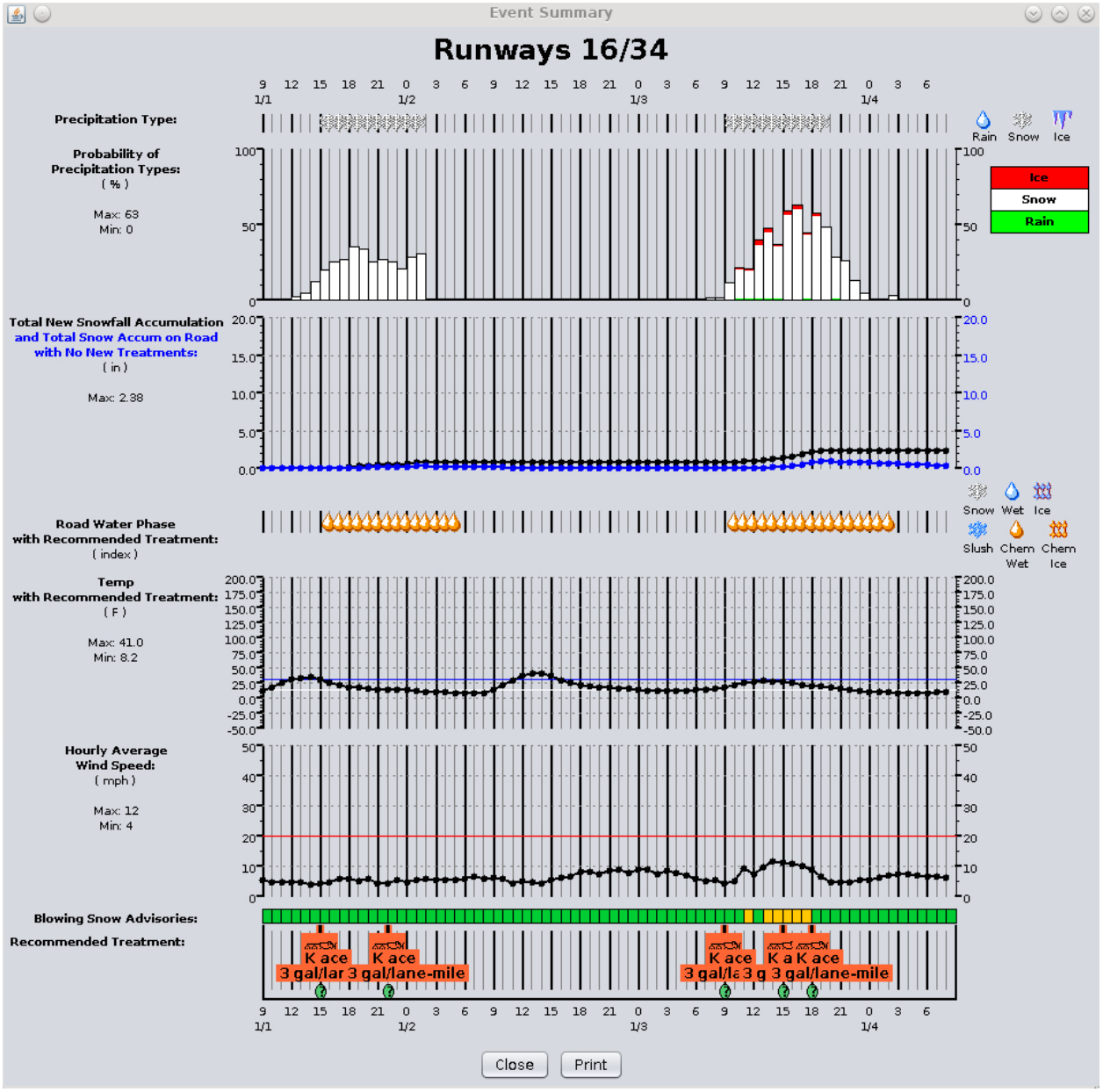

Figure 17: MDSS event summary forecast starting at 9am on January 1, 2015

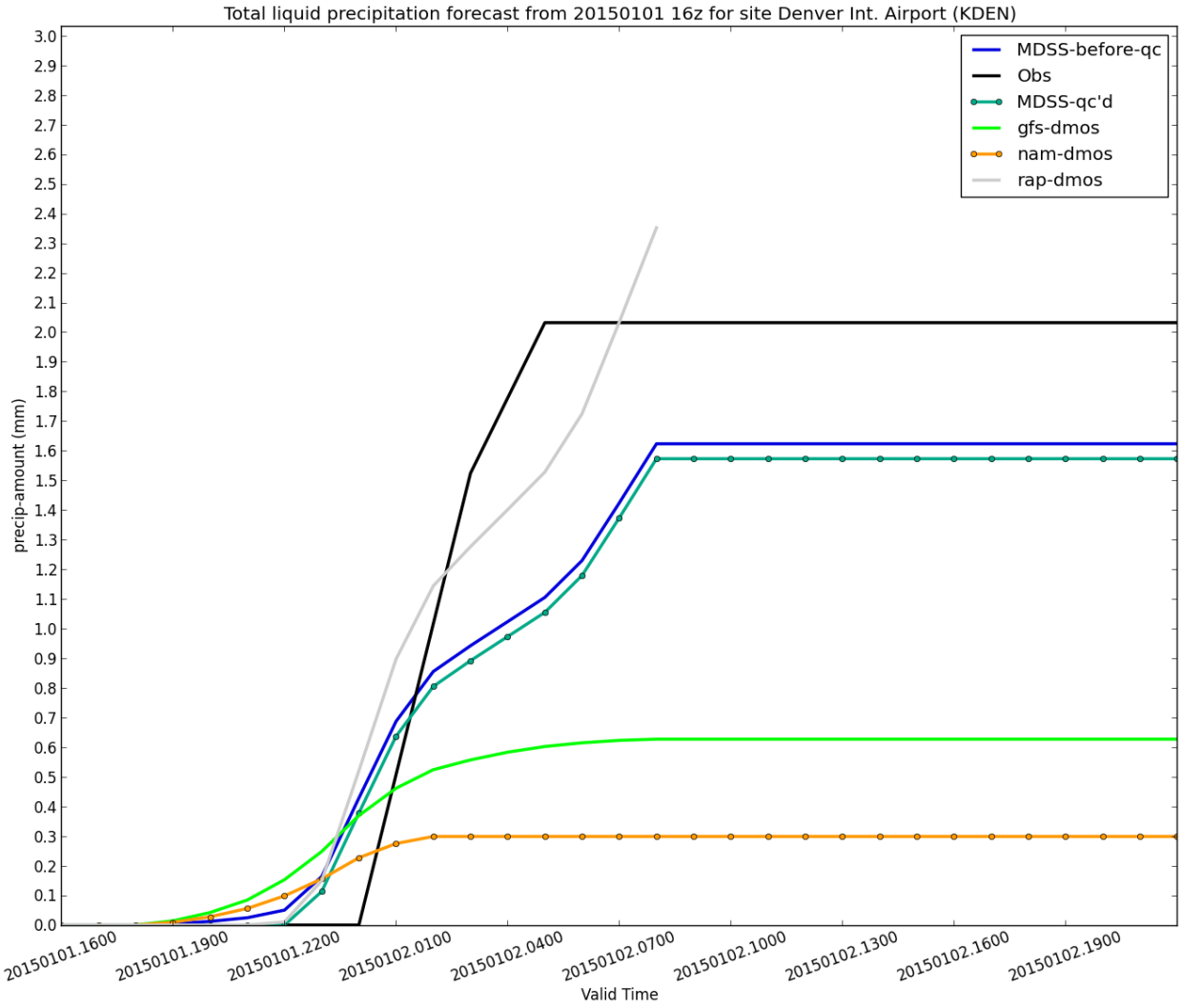

Figure 18: MDSS liquid precipitation forecast vs. observations for Denver Int. Airport (KDEN). Forecast generated at 9am on January 1, 2015

Case studies summary.

The storm event case studies examined here highlight a range of different types of winter weather events and also highlight times when MDSS performed well and other times when it performed poorly. With regard to the snow-fall forecast, three of the cases (Nov 11th, January 1st and February 2nd) highlight potential issues in the system that can be fixed. Research will be done to examine better ways to qc (quality control) out low precipitation amounts during very cold storms events. Additional research will be done to examine the MDSS snow-ratio algorithm and determine how to prevent it from producing snow-ratios that are too low or too high. Research will also be done to improve the static model weights that are used for the MDSS precipitation forecasts. The case studies also highlight that having a human in-the-loop, i.e. Weathernet does improve the overall guidance for most events, especially at the times when the MDSS pavement temperature forecast is off and snow may accumulate on the runways earlier than MDSS indicated. The Weathernet guidance also helped with timing of precipitation start and stop times for certain cases. Overall for the bigger events, MDSS did quite well forecasting precipitation-types, precipitation start and stop times and total snow amounts.