The Maintenance Decision Support System (MDSS) Project

TECHNICAL PERFORMANCE ASSESSMENT REPORT

COLORADO FIELD DEMONSTRATION WINTER 2004-2005

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23 September 2005

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RELEASE NOTES

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<tr>
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ACRONYM GLOSSARY

AOTR – Agreement Officer’s Technical Representative
ASOS – Automated Surface Observing System (NWS)
AVN – National Weather Service Model
AWOS – Automated Weather Observing System (FAA)
CRREL – U.S. Army Cold Regions Research and Engineering Laboratory
C – Degrees Celsius
CDOT – Colorado Department of Transportation
DIA – Denver International Airport
DMOS – Dynamic Model Output Statistics
DOT - Department of Transportation
DOY – Day Of the Year
DSS – Decision Support System
EMC – Environmental Modeling Center
EMFP - Ensemble Model Forecast Provider
ESRI – Environmental Systems Research Institute
ESS - Equitable Skill Score
Eta – National Weather Service Model
ETL – NOAA, Environmental Technology Laboratory
FAA – Federal Aviation Administration
FHWA – Federal Highway Administration
FSL – NOAA, Forecast Systems Laboratory
FTP – File Transfer Protocol
GFS – Global Forecast System Weather Service Model
GPS/AVL – Global Positioning System/Automated Vehicle Location
GRIB – Gridded Binary
HADS - Hydrometeorological Automated Data System of the NWS
HRDO – Office of Research and Development Operations (FHWA)
HOTO - Office of Transportation Operations
ITS – Intelligent Transportation System
JPO – Joint Program Office (FHWA)
LAPS – Local Analysis and Prediction System
LDADS – Local Data Acquisition and Dissemination System
LDM – Local Data Manager
MADIS – Meteorological Assimilation Data Ingest System (NOAA/FSL)
MAE – Median Absolute Error
MDSS - Maintenance Decision Support System
MDSS FP -Maintenance Decision Support System – Functional Prototype
METAR – Meteorological Surface Observation including ASOS and AWOS sites
MIT/LL - Massachusetts Institute of Technology - Lincoln Laboratory
MM5 – Mesoscale Model – Version 5 (NCAR & Penn State)
MOS – Model Output Statistics
NCEP - National Centers for Environmental Prediction
NEXRAD – NEXt generation RADar program
NSF – National Science Foundation
NSSL – NOAA, National Severe Storms Laboratory
NOAA – National Oceanic and Atmospheric Administration
NCAR - National Center for Atmospheric Research
NVD - Non-Verifiable Data
NWP – Numerical Weather Prediction
NWS – National Weather Service
OCD – Operational Concepts Description
QPE – Quantitative Precipitation Estimate
QPF – Quantitative Precipitation Forecast
RCTM – Road Condition & Treatment Module
RMSE – Root Mean Squared Error
ROP – Rules of Practice
RTVS – Real Time Verification System (RTVS)
RUC – Rapid Update Cycle (NWS weather prediction model)
RWFS – Road Weather Forecast System
RWIS – Road Weather Information System
RWMP - Road Weather Management Program
SNTHERM-RT – Heat balance model used to predict road temperatures
STWDSR - Surface Transportation Weather Decision Support Requirements
UTC – Universal Time Coordinated (same as Greenwich Mean Time)
VAMS - Value Added Meteorological Services
WIST-DSS - Weather Information for Surface Transportation Decision Support System
WMO – World Meteorological Organization
WRF – Weather Research & Forecasting Model
Z – Zulu time (same as Greenwich Mean Time)
NOTICE

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The Federal Highway Administration (FHWA) Office of Transportation Operations, Road Weather Management Program, funded this project. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the U.S. Department of Transportation.

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1 PURPOSE

The technical performance results of the prototype Maintenance Decision Support System (MDSS) from the winter 2004-2005 Colorado field demonstration are described in this document. Recommendations for future improvements are also highlighted throughout the document. The field demonstration officially started on 15 October 2004 and ended on 3 May 2005. Many different aspects of the MDSS are discussed including bulk statistics on its performance during the entire field demonstration and case studies of individual events. Individual components of the system are evaluated, including the Road Weather Forecast System (RWFS), road temperature module (SNThERM-RT), road treatment module, mesoscale weather models, and display application.

2 INTENDED AUDIENCE

The intended audiences for this document are persons directly involved in the MDSS 2004-2005 field demonstration including the Federal Highway Administration (FHWA), E-470 Public Road Authority, Colorado Department of Transportation (CDOT), national laboratories, stakeholders with an interest in the MDSS project (private sector meteorological service providers and state Departments of Transportation (DOTs), and casual observers who wish to follow developments related to winter road maintenance technologies. It is recommended that the reader have a working knowledge of meteorological verification methods and statistical analysis metrics.

3 BACKGROUND

This MDSS Project is part of a federal procurement for research projects and deployment advocacy, which is funded through the Intelligent Transportation System (ITS) Joint Project Office (JPO) of the FHWA.

It is anticipated that components of the prototype MDSS developed by this project will be enhanced, integrated with other operational components, and deployed by road operating agencies, including state DOTs, and generally supplied by commercial weather service providers.

Four national research centers participated in the development of the prototype MDSS in 2004-2005. The participating national labs include:

- Army Cold Regions Research and Engineering Laboratory (CRREL)
- National Center for Atmospheric Research (NCAR)
- Massachusetts Institute of Technology - Lincoln Laboratory (MIT/LL)
- National Oceanic and Atmospheric Administration (NOAA) Forecast Systems Laboratory (FSL)
4 RELATED DOCUMENTS

For additional information on the MDSS Project, the reader is directed to the related project documents and web sites listed in Table 4.1.

Table 4.1. MDSS Project Related Documents

<table>
<thead>
<tr>
<th>Document and/or Web Sites</th>
<th>Primary Source</th>
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<tr>
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<td>Federal Highway Administration</td>
</tr>
<tr>
<td><a href="http://www.itsdocs.fhwa.dot.gov/ipodocs/repts_te/9dc01!.pdf">http://www.itsdocs.fhwa.dot.gov/ipodocs/repts_te/9dc01!.pdf</a></td>
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<tr>
<td>STWDSR— Operational Concept Description (OCD) Version 2.0</td>
<td>Federal Highway Administration</td>
</tr>
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<td>Maintenance Decision Support System (MDSS) Project Web Site at FHWA:</td>
<td>Federal Highway Administration</td>
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<td><a href="http://ops.fhwa.dot.gov/weather/mitigating_impacts/programs.htm#3">http://ops.fhwa.dot.gov/weather/mitigating_impacts/programs.htm#3</a></td>
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<td>Maintenance Decision Support System (MDSS) Project Web Site at NCAR:</td>
<td>National Center for Atmospheric Research</td>
</tr>
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<td><a href="http://www.rap.ucar.edu/projects/rdwx_mdss/index.html">http://www.rap.ucar.edu/projects/rdwx_mdss/index.html</a></td>
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5 METHODS

This document provides prototype MDSS results from the winter 2004-2005 MDSS field demonstration. Objective analyses of the weather forecasts and subjective analyses of the road treatment recommendations were performed. In addition, analyses of the road temperature model, rules of practice, and mesoscale weather model components are provided. Where possible, results are summarized and recommendations provided as guidance for those planning to implement MDSS components or similar technologies.

Obtaining sufficient, high quality verification data, especially precipitation information, continues to be a challenge for this project and similar efforts. Issues related to verification data limitations are described throughout this document.

Surface weather observation quality from standard road weather information systems was assessed in 2003 via coincident observations of state and road parameters (Bernstein et. al., 2003). Differences apparent in the observations themselves set an acceptable threshold of deviation of the forecast from the observations, or a lower bound for the accuracy one can expect from the MDSS forecasts; for if the observations can only be measured within a certain tolerance, then differences between such observations and the MDSS forecasts are attributable to uncertainty in the observations themselves.

Objective verification is achieved via direct comparisons of MDSS forecasts and reliable observations from National Weather Service and roadside Environmental Sensor Stations (ESS). These results are presented through diagrams of root mean squared error (RMSE), median absolute error (MAE), and bias for state parameter fields (e.g. air temperature, dewpoint, and wind speed), as well as road and bridge temperature. The complexity and subjective nature of the road treatment verification recommendations lend themselves well to a case study approach. This approach places the recommendations into the necessary context of the forecast itself, as well as the actual conditions that occurred. Contrast between the forecast and reality are often at the root of differences between the recommended and actual treatments. Several case studies are presented herein including a number of different snow events with varying total snow depth accumulations and the air temperature at which they occurred.

6 MDSS VERIFICATION ROUTES

A total of 12 plow routes were configured in the MDSS for the 2004-2005 field demonstration. The plow routes include six along the entire E-470 corridor near Denver, Colorado, three on I-25 south of Denver, three on I-70 just west of Denver up to Floyd Hill, and three on I-70 in the mountains from Vail Pass to Wolcott, Colorado. The selected routes are shown in Figs. 6.1 and 6.2, and a corresponding description of the routes is provided in Table 6.1. Separate treatment plans were generated by the MDSS prototype for each of the plow routes. Much of the verification will focus on the E-470 plow route labeled “Route D” (northeastern section of E-470 near Denver International Airport (DIA), due to the proximity of an RWIS, the DIA METAR and a GEONOR precipitation gauge also located at DIA (see Fig. C.1, Appendix C).
Fig 6.1: Map of E-470 routes supported by the MDSS prototype during the winter of 2004-2005 Colorado field demonstration. Key observation sites are annotated. Note, there is no route C in the E-470 system.
Fig. 6.2: Map of CDOT routes supported by the MDSS prototype during the winter of 2004-2005 Colorado field demonstration.
Table 6.1. Colorado Maintenance Routes for the MDSS Field Demonstration

<table>
<thead>
<tr>
<th>Region</th>
<th>Segment Number</th>
<th>Description</th>
<th>Elevation (m)</th>
<th>Surface Type</th>
</tr>
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<tr>
<td>E-470</td>
<td>9</td>
<td>Plaza A</td>
<td>1772</td>
<td>Asphalt</td>
</tr>
<tr>
<td>E-470</td>
<td>10</td>
<td>Smokey Hill</td>
<td>1854</td>
<td>Asphalt</td>
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<td>E-470</td>
<td>11</td>
<td>Colorado Blvd</td>
<td>1578</td>
<td>Asphalt</td>
</tr>
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<td>E-470</td>
<td>12</td>
<td>Platte River</td>
<td>1527</td>
<td>Asphalt</td>
</tr>
<tr>
<td>E-470</td>
<td>13</td>
<td>6th Ave Parkway</td>
<td>1687</td>
<td>Asphalt</td>
</tr>
<tr>
<td>E-470</td>
<td>14</td>
<td>MSS-D</td>
<td>1598</td>
<td>Asphalt</td>
</tr>
<tr>
<td>Denver South</td>
<td>1</td>
<td>I-25 at C-470 West</td>
<td>1829</td>
<td>Concrete</td>
</tr>
<tr>
<td>Denver South</td>
<td>2</td>
<td>I-25 at C-470 East</td>
<td>1829</td>
<td>Concrete</td>
</tr>
<tr>
<td>Denver South</td>
<td>7</td>
<td>I-25 at Surrey Ridge</td>
<td>1890</td>
<td>Concrete</td>
</tr>
<tr>
<td>Denver South</td>
<td>8</td>
<td>I-25 Exit 191</td>
<td>1844</td>
<td>Concrete</td>
</tr>
<tr>
<td>Denver West</td>
<td>3</td>
<td>I-70 at Rooney Road</td>
<td>1886</td>
<td>Asphalt</td>
</tr>
<tr>
<td>Denver West</td>
<td>4</td>
<td>I-70 at Genesee</td>
<td>2255</td>
<td>Asphalt</td>
</tr>
<tr>
<td>Denver West</td>
<td>6</td>
<td>I-70 at Floyd Hill</td>
<td>2414</td>
<td>Asphalt</td>
</tr>
<tr>
<td>Vail Pass</td>
<td>5</td>
<td>Vail Pass</td>
<td>3170</td>
<td>Asphalt</td>
</tr>
<tr>
<td>Vail Pass</td>
<td>15</td>
<td>Dowd Junction</td>
<td>2432</td>
<td>Asphalt</td>
</tr>
<tr>
<td>Vail Pass</td>
<td>16</td>
<td>Wolcott</td>
<td>2164</td>
<td>Asphalt</td>
</tr>
</tbody>
</table>

Road condition data were only collected for a subset of the total routes supported by the prototype MDSS in 2005. This decision was based on the need to collect quality data and the fact that obtaining detailed road condition data throughout a storm is difficult, manually intensive, expensive, and time consuming. Road condition data were collected from E-470 along all the six E-470 plow routes (see Fig. 6.1). Vail Pass was added to the MDSS strictly for internal evaluation. CDOT personnel from the Vail Pass garage were not involved in the MDSS demonstration and the pavement segment that contained the Vail pavement temperature sensor was not routinely maintained.

7 MDSS SYSTEM CONFIGURATION

All of the MDSS core technical components (e.g., RWFS, RCTM, and data server) were operated centrally at NCAR in Boulder. A server at NCAR communicated (via the Internet) with local PCs running the display application at E-470 headquarters and maintenance facilities, and at the CDOT maintenance garages responsible for the plow routes supported by the MDSS. Supplemental weather forecast models were run at FSL in Boulder and the data forwarded to NCAR for inclusion in the RWFS. E-470 and CDOT RWIS data were provided to NCAR via FSL as part of the Meteorological Assimilation Data Ingest System (MADIS) program. E-470 data were included in MADIS in late summer 2004 and CDOT RWIS data became available starting in late January 2005. The delay in obtaining CDOT RWIS data was the result of a CDOT RWIS data server upgrade that was performed throughout the fall of 2004.
A simplified illustration of the MDSS prototype system configuration is provided in Fig. 7.1.

Fig. 7.1. Depiction of the prototype MDSS configuration for the winter 2004-2005 Colorado field demonstration. All network MDSS connections to the sites were via the internet.

7.1 Supplemental Numerical Weather Prediction Models

For the 2004-2005 prototype MDSS demonstration, FSL configured multiple, high-resolution models to run over the demonstration region. The model domain is shown in Fig. 7.2. The configuration consisted of running MM5 and WRF every hour. The WRF was run out to 18 hours and the MM5 was run out to 24 hours. Computing resources did not permit both models to run out to 24 hours as was anticipated while planning the demonstration. The hourly model output was blending into the RWFS using a “time-lagged” ensembling technique. For example, a 6-hr (hour) forecast used the current 6-hr forecast, as well as the 7-hr forecast, and the 8-hr forecast from the previous model cycles. It was anticipated that this method would provide consistency between MDSS updates and minimize large changes in the forecast.
The FSL modeling system incorporated a diabatic initialization (a.k.a. *hot start*) scheme to improve predictions of clouds and precipitation in the early periods (first 6 hours) of the forecast. Other methods for diabatic initialization are used by the research community, but are too computationally intensive to use in real time. The Local Analysis and Prediction System (LAPS) *hot start* initialization method was used for the MM5 and WRF models. A *hot start* initialization is a method to generate cloud water and precipitation processes at the start of the model run.

Information on the MM5 and WRF models can be found at:

MM5: [http://www.mmm.ucar.edu/mm5/mm5-home.html](http://www.mmm.ucar.edu/mm5/mm5-home.html)

WRF: [http://wrf-model.org/](http://wrf-model.org/)

The lateral boundary conditions for both models were provided by the Eta model, which is run by the NWS National Centers for Environmental Prediction (NCEP). The Eta model was delivered to NWS field offices and FSL four times daily.

The supplemental modeling configuration used for the Colorado MDSS field demonstration is summarized in Table 7.1.
Table 7.1. Configuration of the MDSS Supplemental Models

<table>
<thead>
<tr>
<th>Forecast Model</th>
<th>Boundary Condition Source</th>
<th>Forecast Period</th>
<th>Grid Spacing</th>
<th>Update Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRF</td>
<td>NWS: Eta</td>
<td>18 hours</td>
<td>12-km</td>
<td>1-hr</td>
</tr>
<tr>
<td>MM5</td>
<td>NWS: Eta</td>
<td>24 hours</td>
<td>12-km</td>
<td>1-hr</td>
</tr>
</tbody>
</table>

The mesoscale models (WRF and MM5) ran every hour providing a new forecast, out 18-hrs and 24-hrs respectively, to the RWFS. Even though the fine scale models were run hourly, the MDSS updated only every 3 hours. Since the hourly mesoscale model forecasts ran out to at least 18 hours, this ensured that there were forecasts available from the fine scale models out to 15 hours at all times with the 3 hour update cycle for MDSS.

FSL’s Experimental Rapid Update Cycle (RUC) Model was also one of the models utilized by the RWFS. The RUC data were acquired by NCAR from FSL. No special runs were generated to provide the RUC model as it runs daily, every three hours, as part of ongoing NOAA and FAA research programs. The domain of the RUC model is the continental U.S. with a grid spacing of 20-km. For information on the RUC model, please see:


### 7.2 MDSS Prototype Optimization Period

The RWFS is tasked with ingesting reformatted meteorological data (observations, models, statistical data, climate data, etc.) and producing meteorological forecasts at user defined forecast sites and forecast lead times. The forecast variables output by the RWFS are used by the RCTM to calculate the road surface temperature and to calculate a recommended treatment plan. In order to achieve this goal, the RWFS generates independent forecasts from each of the data sources using a variety of forecasting techniques.

A single consensus forecast from the set of individual forecasts is provided for each user defined forecast site (e.g., plow route) based on a processing method that takes into account the recent skill of each forecast module. This consensus forecast is nearly always more skillful than any component forecast. The RWFS is designed to optimize itself using available observations near the routes (e.g., RWIS, METARS). The forecast modules that perform the best are given more weight over time. In addition, Dynamic Model Output Statistics (DMOS) are calculated weekly using observations and model output. The DMOS process is used to remove model biases. The optimization period of the RWFS is approximately 90-100 days. Observations and weather model data were collected starting on 18 August 2004. Forecast operations began on 18 October 2004. Because of this, the forecasts during the first month of the demonstration were not fully optimally
tuned. However, within a month after that time, the system had an adequate learning period.

For more information on the RWFS as configured for the winter 2004-2005 demonstration, the reader is directed to Appendix A of the MDSS Prototype Release-3.0 Technical Description (see reference in Table 4.1).

8 DATA COLLECTION PROCESS

The technical performance assessment of the MDSS was performed by the MDSS national lab team. A critical component of the verification process was the collection of weather, road condition, and actual treatment data in order to make this task possible. NCAR was responsible for archiving all the surface observations throughout the field demonstration and E-470 personnel were primarily responsible for collecting the road condition and treatment data using their own data collection forms. CDOT also recorded the treatments they performed, but resources were insufficient to analyze these data. Analysis of the MDSS treatment recommendations was confined to the E-470 routes.

The MDSS field demonstration began following a demonstration readiness meeting on 12 October 2004. A daily summary of the weather for the Denver area, system issues and software updates is provided in Appendix B.

The first significant weather event occurred on 31 October 2004 and the last major weather event occurred on 10 April 2005. The demonstration officially began on 15 October 2004 and ended on 3 May 2005. There was good diversity in the types of weather events that impacted Colorado during this period. The Denver metro area alone experienced heavy and light snow events, mixed rain and snow, brief freezing rain, and bridge frost events. In addition, the routes along I-70 near Vail Pass experienced several significant blowing and drifting snow events. There were 16 notable winter weather event days during the course of the 183 day demonstration, including ten light, five moderate, and one heavy snow event.

The MDSS operated quite well throughout the period; however, there were a few brief outages of the RWFS when the NCAR lab lost power. There were also a few additional periods when the supplemental mesoscale models from FSL were unavailable. On a few occasions (estimated to be less than five 3-hr periods), the MDSS display malfunctioned when it was unable to handle bad data resulting from run time faults in the road temperature model. The exact dates and times of most of these outages are listed in the storm summary in Appendix B. An evaluation of the impact of these models on the MDSS performance is provided later in this report.

8.1 Supplemental Data Collection

The goal of the data collection process was to capture the evolution of weather and road conditions during the life cycle of winter storm events near the MDSS demonstration
routes. Verification data were obtained and archived from several sources near the selected MDSS routes.

Several data collection methods were used this year including:

a) Manual data collection of actual road conditions and treatments using standard E-470 snow removal event forms  
b) Automated collection of weather data (local ASOS, AWOS, and RWIS)

8.2 Data Sources: Weather Observations

The following weather observation data sources were used for verification and analysis:

a) Colorado DOT and E-470 RWIS  
b) NWS ASOS/AWOS  
c) Local observer surface data  
d) Weather satellite  
e) Weather radar  
f) NWS storm summaries  
g) E-470 personnel observations  
h) GEONOR precipitation gauge (Denver International Airport)  
i) Denver Urban Drainage and Flood Control District precipitation observations

8.3 Data Sources: Road Condition Observations

The following road condition data sources were used for verification and analysis:

a) Colorado DOT and E-470 road temperature sensors  
b) E-470 personnel observations  
c) NCAR personnel observations

8.4 Data Sources: Actual Treatment Performed

The following data sources were used to obtain data describing the actual winter maintenance treatments:

a) E-470 standard snow removal event forms

8.5 Verification Data Forms

In order to fully estimate the weather and road conditions performed during each event, it was helpful to use E-470’s standard snow removal event forms, which were completed
during each weather event. The forms helped capture the following information about weather and road conditions for certain times and cases:

- Date
- Time
- Route
- Treatment performed (suggested by supervisor)
  - Chemicals used (MgCl₂, solids, liquids, etc.)
  - Chemical amount (tonnage and/or pounds per lane mile or gallons per lane mile)
  - Plowing performed
- Estimated road condition per route
  - Wet, dry, icy, snow-packed, blowing snow, snow depth, slush, rain, freezing rain, frost, etc.
  - Road temperature (if available)
- Weather conditions along route
  - Precipitation type, precipitation start and stop times, blowing snow, snow depth, frost, air temperature, wind speed, etc.

9 MDSS ENHANCEMENTS FOR WINTER 2004-2005

Using the winter 2003-2004 post-demonstration evaluations from Iowa, technical performance results, and the lessons learned from meetings with Iowa DOT and support personnel, limited system development activities were performed prior to the start of the Colorado demonstration. Enhancements to the MDSS are listed below.

**Bridge Frost Potential:** NCAR worked with Tina Greenfield of Iowa State University (now with Iowa State Department of Transportation) to refine and implement a bridge frost product. The product uses SNTHERM-BT (bridge temperature version) to calculate bridge pavement surface temperatures. The RWFS forecasted air temperature, dewpoint temperature, wind speed, pressure, precipitation rate, and the Iowa State algorithm are used to calculate frost deposition. The forecast data were interpolated for each bridge site to create a minute-by-minute forecast over the entire forecast period for each variable. Because the occurrence of frost is very sensitive to small errors in environmental conditions, that is, a small change in air or dewpoint temperature can result in a switch from favorable to unfavorable frost conditions, a Monte-Carlo statistical technique was applied to the primary data inputs (bridge, air and dewpoint temperatures, and wind speed) to calculate the uncertainty in those predictions. The variations used are based on appropriate standard deviations for each variable. An interest function is applied to the frost depth returned from the Iowa State algorithm and a weighted average of these interest values is calculated. The weight given to each frost occurrence estimate emulates the statistical probability of that combination of events happening. The likelihood of bridge frost is calculated and mapped to the MDSS alert categories (OK, marginal, poor, and
extreme). The Bridge Frost Potential product was implemented in the RCTM. The MDSS display application was also enhanced to show the output.

Configuration for Colorado: The RWFS and RCTM components were reconfigured to operate over Colorado as the system was previously demonstrated in Iowa. The primary MDSS configuration changes are listed below:

- Updated plow route times to match E-470’s operations
- Refined the maximum and minimum chemical application rates for E-470
- Added bridge temperature forecasts (from an actual bridge if it existed, or simulated if not) for each applicable RWIS site
- Utilized data from the E-470, CDOT, and Northwest Parkway\(^1\) environmental sensor stations

Display Application Changes: The MDSS display application was changed to cover Colorado routes. Changes included:

- Added Colorado State view
- Added new topographic maps
- Added new route views
- Added bridge temperature data
- Added E-470, CDOT, and Northwest Parkway Authority RWIS sites
- Added placeholders for new chemicals on the display (CaMg Acetate, Ice Slicer®, Ice Ban®, and Caliber®)

Snow Water Ratio Algorithm: A dynamic snow-water ratio algorithm was implemented in the RWFS. The algorithm, which was based on research conducted by CRREL, calculates the snow-water ratio using liquid equivalent precipitation amount, surface air temperature, and wind speed. Wind speed reduces the snow-water ratio due to densification of the ice crystals. Prior to this enhancement, the MDSS used a static 10:1 snow-water ratio, which was known to be deficient in some circumstances, but not addressed prior to the winter season demonstration due to insufficient resources and time.

10 OVERALL PERFORMANCE RESULTS

In this section, performance results are described for the entire winter 2004-2005 Colorado field demonstration for specific components of the MDSS. Bulk statistics based on the weighted average root mean square error (RMSE), median absolute error (MAE) and bias (forecast minus observation) are calculated. The weighted average RMSE is calculated in the following manner: for each lead time, RMSE is calculated for each site and then weighted based on the total number of valid errors for that site. The RMSE values (for each site) are then summed over all sites and divided by the sum of the errors for each site.

\(1\) The Northwest Parkway is a new toll road that connects E-470 to Colorado highway 36 in Broomfield, Colorado. The Parkway had one RWIS and these data were provided to MADIS and utilized by the MDSS.
In addition, in order to get a new look at how well the MDSS performs in complex terrain, the statistics within each subsection are stratified by region including: E-470 sites, Colorado plains sites, and Colorado mountain sites.

10.1 RWFS Forecast Modules

The RWFS was configured to utilize and integrate ten different forecast modules for the winter 2004-2005 demonstration. Models that were ingested into the RWFS included the Eta, GFS, MM5, RUC and WRF. As described in Section 7.1, the MM5 and WRF models were initialized using the NWS Eta model for boundary conditions and run hourly. MM5 and WRF forecasts from the current run and previous two runs (valid at the same time) were then utilized. Aviation Model Output Statistics (MAVMOS) were also used as input, and Dynamic Model Output Statistics (DMOS) were calculated within the RWFS for each of the model inputs. The ten weather forecast modules that were used to predict the weather parameters for each MDSS forecast point were:

1) NWS Aviation MOS (MAVMOS)
2) Eta DMOS
3) GFS DMOS
4) MM5 Eta4 (run from 4 hours previous)
5) MM5 Eta3 (run from 3 hours previous)
6) MM5 Eta (run from 2 hours previous, the most current run)
7) WRF Eta4 (run from 4 hours previous)
8) WRF Eta3 (run from 3 hours previous)
9) WRF Eta (run from 2 hours previous, the most current run)
10) RUC DMOS

The RWFS integration process independently optimized the forecasts based on recent skill at each prediction site for each parameter and forecast lead time, except for precipitation. Forecast modules with the most skill get more weight in the RWFS integration process that generates the consensus forecast. Due to the lack of accurate winter precipitation measurements, the probability of precipitation (POP) and quantitative precipitation forecast (QPF) consensus output were calculated using fixed weights. The method chosen to select the weights for POP and QPF are described in Section 10.5. Due to the lack of real-time insolation (incoming solar radiation) measurements, a fixed weighted blend of insolation values from selected forecast modules was also used as described in Section 10.6. More information on the RWFS can be found in the MDSS Technical Description (see Table 4.1 for reference information).

The RWFS also applied a Forward Error Correction (FEC) which is used to ensure that the forecasts produced by the RWFS more accurately reflect the current conditions in the near term. The forecasts valid at the current time are forced to match the available observations. Then, in the first forecast hours, the forecast time series is forced to trend toward, and blend seamlessly into, the RWFS consensus forecast.
10.2 Overall Performance of the Road Weather Forecast System

10.2.1 Performance Assessment of Meteorological Variables

The RWFS consensus forecast was compared to the forecasts from the individual models included in the ensemble in order to discern whether the RWFS statistical post processing methods and techniques added skill.

Error Analysis

Bulk statistics were computed for the ten individual models listed in section 10.1 and the RWFS final consensus forecast for four meteorological variables (air temperature, dewpoint temperature, wind-speed and cloud cover). The results are based on average RMSE and bias per lead time (out 48 hours) of forecasts initiated at 18 UTC for the entire season (1 November 2004 to 15 April 2005). As mentioned earlier, and as will be the case for all the statistics in this section, the results were stratified by regions, including: E-470 sites only (5 sites), Colorado plains sites (176 sites), and Colorado mountain sites (119 sites). Note: cloud cover RMSE was calculated over the Colorado plains and mountain sites only due to a lack of observations for the E-470 sites.

For all four variables the RWFS performed well with the consensus forecasts having lower or equivalent RMSE values compared to the individual forecast module components for a majority of lead times, as well as for each region (E-470: Figs. 10.1-10.3, COplains: Figs. 10.4-10.7, COMtns: Figs. 10.8-10.11). Forward Error Correction (FEC), which is applied to all the verifiable variables (variables that have corresponding observations), significantly reduces the RMSE within the first 6 hours and is most evident for air temperature, dewpoint temperature, and cloud cover. In general, there is a more pronounced difference in skill (i.e. larger spread among the forecasts) between the final consensus forecast and its components for air temperature and dewpoint temperature than for wind speed and cloud cover (Figs. 10.1-10.2, 10.4-10.5, 10.8-10.9). There are also subtle differences in skill between some of the forecast variables in the different site regions.

The difference between the final consensus forecast and its components for longer lead times is less pronounced for the E-470 sites. This may be the result of RMSE being calculated over far fewer sites than the Colorado plains and mountain regions. For wind speed, the RMSE of the consensus forecast over the E-470 sites is equivalent to the Eta through 27 hours and slightly better thereafter (Fig. 10.3). For the Colorado mountain sites the RMSE for wind speed is slightly worse than the RUC through 21 hours out and better thereafter (Fig. 10.10). This may reflect the difficulty in forecasting wind speed in complex terrain. For cloud cover, there is very little difference in forecast skill between the final consensus forecasts and the best components (Eta and GFS) for a majority of lead times with the exception being within the first 6 hours where FEC makes the consensus forecasts better (Figs. 10.7 and 10.11).
Fig. 10.1: Weighted average air temperature RMSE computed based on 18 UTC initialization forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the E-470 sites are shown.

Fig. 10.2: Weighted average dewpoint temperature RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the E-470 sites are shown.
Fig. 10.3: Weighted average wind speed RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the E-470 sites are shown.

Fig. 10.4: Weighted average air temperature RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado plains sites are shown.
Fig. 10.5: Weighted average dewpoint temperature RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado plains sites are shown.

Fig. 10.6: Weighted average wind speed RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado plains site are shown.
Fig. 10.7: Weighted average cloud cover RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado plains site are shown.

Fig. 10.8: Weighted average air temperature RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado mountain sites are shown.
Fig. 10.9: Weighted average dewpoint temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado mountain sites are shown.

Fig. 10.10: Weighted average wind speed RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado mountain sites are shown.
Fig. 10.11: Weighted average cloud cover RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005). The consensus forecast (black line) and the individual forecast module components for the Colorado mountain sites are shown.

The oscillations seen primarily in the air and dew point temperatures (Figs. 10.4, 10.5, 10.8, and 10.9) are an artifact of how the RWFS tunes its forecasts independently for each hourly forecast. When the NWS MOS products are available (every 3 hours), the forecasts are improved. In between the 3 hourly MOS data, the forecasts are slightly less accurate. The data could be smoothed to provide a more pleasing presentation by interpolating the MOS data to produce hourly data. This technique will be implemented for the 2005-2006 demonstration.

Results Summary: The statistical methods and techniques utilized by the RWFS do improve the predictions on average for all verifiable parameters. It is clear from the analyses that no single model performs better for all parameters; therefore a blend of weather models will provide better results.

Bias Analysis

Overall, the RWFS exhibits no significant bias for the four meteorological state variables examined (Figs. 10.12-10.20). There are slight trends by region, including a very minor cold and dry bias (less than 0.5°C each) in air temperature and dewpoint temperature for all of the regions (Figs. 10.12-10.13, 10.15-10.16, 10.19-10.20), and a small positive bias (less than 0.25 m/s) for wind speed in the plains and mountains sites (Figs. 10.17, 10.21).
However, the magnitude of these biases is very small and could be considered negligible. Further, there is very little bias in the cloud cover forecast for the Colorado plains (Fig. 10.18). In the mountains the system seems to slightly underestimate cloud cover during the day and overestimate cloud cover at night (Fig. 10.22).

**Fig. 10.12:** Weighted average air temperature bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the E-470 sites.
Fig. 10.13: Weighted average dewpoint temperature bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the E-470 sites.

Fig. 10.14: Weighted average wind speed bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the E-470 sites.
Fig. 10.15: Weighted average air temperature bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado plains sites.

Fig. 10.16: Weighted average dewpoint temperature bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado plains sites.
Fig. 10.17: Weighted average wind speed bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado plains sites.

Fig. 10.18: Weighted average cloud cover bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado plains sites.
Fig. 10.19: Weighted average air temperature bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado mountain sites.

Fig. 10.20: Weighted average dewpoint temperature bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado mountain sites.
Fig. 10.21: Weighted average wind speed bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado mountain sites.

Fig. 10.22: Weighted average cloud cover bias computed from the 18 UTC RWFS output for the entire demonstration season (1 November 2004 – 15 April 2005) for the Colorado mountain sites.
Results Summary: The RWFS exhibits no significant bias for the analyzed weather variables. There is a slight cold bias for air temperature, a slight dry bias for dew point, and some diurnal trends in wind speed and cloud cover.

10.2.2 Verification of Daily Maximum and Minimum Air Temperatures

A forecast could appear to be poor when verified on an hourly basis (as done in the case study approach reviewed in Section 11) if the times of peak heating and cooling are slightly shifted. Thus, it is also worth examining the system on a daily basis rather than an hourly basis to see how well the maximum and minimum air temperatures are predicted by the RWFS. The maximum and minimum values are derived from the hourly time series based on the 18 UTC runs throughout the entire season.

The observations used for the E-470 sites (Figs. 10.23-10.24) were from the RWIS stations located along the roadway. These stations have a precision to the hundredth of a degree for temperature. The observation sites used for the Colorado plains (Figs. 10.25-10.26) and mountains (Figs. 10.27-10.28) consisted of standard NWS ASOS stations, which have a precision only to a tenth of a degree. This is why there is an apparent “clumping” of temperatures on the scatter plots shown in Figures 10.25-10.28.

Results from the MDSS winter 2003-2004 observation quality assessment analysis revealed that the air temperature observations from the RWIS ASOS instruments tended to be within about +/-2.5°C of each other. This represented the measurement uncertainty. In the comparisons done here, for both the maximum and minimum air temperature, 0-23 hr (day one) as well as the 24-47 hr (day two) forecasts, a majority of the points for each region are within +/-4°C of the observations. It is apparent from the plots that for daily maximum air temperatures that are observed below about 5°C, there is a small warm bias in the forecast. Above 5°C, the outliers are greater than +/-2°C and reveal a slight cold bias.

The daily minimum air temperature plots by region are similar to each other, and they reveal a cold bias for air temperatures above 5°C, no significant bias from -5°C to 5°C, and a warm bias at the colder air temperatures less than -5°C.

Overall, the final consensus forecast performs better at the mid-temperature ranges. On the extreme ends of the temperature range, it under-forecasts the warm air temperatures and over-forecast the cold air temperatures. It is also evident that there is not much difference in error between day one and day two.
Fig. 10.23: Scatter plot of the RWFS forecasted maximum air temperature from the daily 18 UTC runs through the entire season, versus the observed maximum air temperature for the E-470 sites.

Fig. 10.24: Scatter plot of the RWFS forecasted minimum air temperature from the daily 18 UTC runs through the entire season, versus the observed minimum air temperature for the E-470 sites.
Fig. 10.25: Scatter plot of the RWFS forecasted maximum air temperature from the daily 18 UTC runs through the entire season, versus the observed maximum air temperature for the Colorado plains sites.

Fig. 10.26: Scatter plot of the RWFS forecasted minimum air temperature from the daily 18 UTC runs through the entire season, versus the observed minimum air temperature for the Colorado plains sites.
Fig. 10.27: Scatter plot of the RWFS forecasted maximum air temperature from the daily 18 UTC runs through the entire season, versus the observed maximum air temperature for the Colorado mountain sites.

Fig. 10.28: Scatter plot of the RWFS forecasted minimum air temperature from the daily 18 UTC runs through the entire season, versus the observed minimum air temperature for the Colorado mountain sites.
Results Summary: The overall skill in predicting maximum and minimum air temperatures was not impressive. The dry Colorado air results in large diurnal temperature swings, often on the order of 20°C per day, and strong, shallow inversions, which are troublesome for forecast models due to insufficient vertical resolution near the surface. Even with its sophisticated statistical post processing, the RWFS had difficulty overcoming the limitation of the forecast models in predicting boundary layer (near surface) air temperatures.

10.2.3 Performance Assessment Based on Conditional RMSE and Bias

Warm and Cold Periods

The end users of the MDSS in its current state are most concerned with its forecast accuracy during times when winter weather has the potential to impact the roadways. For this reason, it is not only important to look at forecasts during cold conditions with overcast skies, precipitation, and high winds, which could potentially cause blowing snow conditions, but also to look carefully at forecasts during cold conditions with clear skies and calm winds when bridge frost may become a hazard.

In order to understand how well the RWFS did during these particular conditions, an analysis was done to examine the air temperature and wind-speed forecasts during certain weather conditions. The forecasts were stratified by air temperature less than 1°C (cold conditions), air temperatures greater than or equal to 1°C (warm conditions), different percentages of cloud cover (cloud conditions), the occurrence of rain and snow (precipitation conditions), and wind speed greater than 10 knots (windy conditions). The RMSE was then calculated at times when only those conditions were observed and compared against the RMSE for all times. In addition, conditional bias was also examined for cold and warm conditions. For RWIS sites which do not report a full range of observations (such as cloud cover and precipitation), nearby ASOS sites were used to get the conditional observations; otherwise the conditional observations are from the actual forecast site being scored.

The same set of forecasts that were used for the bulk statistics (18 UTC data from the RWFS for the entire season) are used for this analysis. In addition to the conditional scores, all the plots show the RMSE calculated over all forecast times (labeled no condition) as a baseline for comparison. The percentage of time these conditions were met compared to the total number of comparisons (labeled total errors in the plots) used for the conditional RMSE and bias calculations are indicated. As these percentages go down, the confidence in the results also declines because the sample data set becomes too small to draw any conclusions that would be statistically significant.

During cold conditions the forecast air temperature errors are larger during the afternoon heating with an increase in error of 1°C for E-470 (Fig. 10.29) and 1.5°C for the Colorado plains sites (Fig. 10.30). For the mountain sites (Fig. 10.31) the increase in error during the heat of the day is smaller and on the order of 0.5°C. It is apparent from
the bias plots for all three regions (Figs. 10.32-10.34) that the forecast is too warm during cold conditions, especially during the middle of the day.

For the warm conditions, the RMSE values for air temperature are very near the \textit{no condition} line most of the time and the diurnal cycle that is evident in the cold cases is not an issue for the warm cases (Figs. 10.35-10.37). There is, however, a cold bias when the air temperatures are greater than 1°C during the overnight to early morning hours. The percentage of errors split between the cold and warm conditions is about 45/55 respectively, for the E-470 and Colorado plains sites, but reverses to 60/40 respectively, for the Colorado mountain sites. In all three cases the percentages are high enough to draw significant conclusions from them.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10_29.png}
\caption{Weighted average air temperature RMSE computed from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during cold conditions only for the E-470 sites.}
\end{figure}
Fig. 10.30: Weighted average air temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during cold conditions only for the Colorado plains sites.

Fig. 10.31: Weighted average air temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during cold conditions only for the Colorado mountain sites.
Fig. 10.32: Weighted average air temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cold conditions only for the E-470 sites.

Fig. 10.33: Weighted average air temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during warm conditions only for the E-470 sites.
Fig. 10.34: Weighted average air temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cold conditions only for the Colorado plains sites.

Fig. 10.35: Weighted average air temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during warm conditions only for the Colorado plains sites.
Fig. 10.36: Weighted average air temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cold conditions only for the Colorado mountain sites.

Fig. 10.37: Weighted average air temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during warm conditions only for the Colorado mountain sites.
Results Summary: The 18 UTC forecasts revealed that a statistically significant warm bias in predicted air temperature occurred during cold periods and a cold bias was found during warm periods. The bias was worse for the Plains sites as compared to the mountain sites. It is likely that the cold biases are the result of an inability of the RWFS and its forecast modules to properly characterize the very shallow layers of cold air (strong inversions) that frequently occur in the high plains of eastern Colorado. The RWFS tends to warm these layers too fast. During warm periods, the RWFS is a bit too cold suggesting that the model blending process tends to produce a consensus average, which tends to pull the prediction toward the mean of the forecast modules.

Techniques will be implemented for the winter of 2005-2006 that will improve the ability of the RWFS to respond to conditions that deviate significantly from average conditions.

Cloudy and Clear Periods

For the cloudy conditions, RMSE of the consensus air temperature forecasts was calculated when the observed cloud cover was less than 20% (clear), 20-50% (scattered), 50-75% (broken), and greater than 75% (overcast).

For the majority of the forecast lead times, the air temperature errors for any of the sky conditions are within +/-1°C of the forecast RMSE for all conditions (Figs. 38-40) suggesting that the errors are not very sensitive to sky conditions. The only exception occurs for the Colorado mountain sites when the observed cloud cover is between 20-50%. For this category, there are large spikes in the error between midnight and 6 a.m.. A cloud cover forecast off by one category can have a large impact on the air temperature forecast in the mountains where radiational cooling is extreme after sunset.

For the E-470 and Colorado plains sites the highest percentage of reports fell in the overcast category which occurred about 50% of the time throughout entire season. The mostly cloudy category had just over 20%, while the clear and partly cloudy categories had just fewer than 15% each. For the Colorado mountain sites the main difference was that the overcast percentage dropped to just over 35% and the clear conditions went up to nearly 50%. The partly cloud and mostly cloudy categories dropped to under 10% each. A possible reason why the E-470 and Colorado plains regions have a higher percentage of overcast conditions could be due to the upslope events that linger longer along the front range of the Colorado Rockies. These events do not affect the mountains sites as much.
Fig. 10.38: Weighted average air temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during cloudy conditions only for the E-470 sites.

Fig. 10.39: Weighted average air temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during cloudy conditions only for the Colorado plains sites.
Fig. 10.40: Weighted average air temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during cloudy conditions only for the Colorado mountain sites.

Results Summary: There was not a strong indication that the air temperature prediction errors were strongly influenced by cloud conditions except for the mountain sites, where poorly predicted clear conditions resulted in large errors on some occasions, which were likely due to strong radiational cooling.

Precipitation Periods

The conditional RMSE air temperature values for specific precipitation conditions were calculated for times when the observing site reported rain or snow. However, these results are based on a relatively limited number of cases making it harder to draw any conclusive conclusions. The rain conditions accounted for less than 3% of the cases, while the snow conditions accounted for less than 15% of the cases for E-470 (Fig. 10.41) and the Colorado plains sites (Fig. 10.42). Statistics were not computed for the Colorado mountain sites due to a lack of reliable, high quality rain and snow observations. Again, for both E-470 and the Colorado plains sites there is an increase in air temperature forecast error for times when rain and snow are reported during the afternoon hours with a maximum difference in error of 2-3°C. The biggest errors occur beyond 12 hours and are larger during times of rain versus snow. These statistics may not be representative because of the low sample size. Some of the error may also stem from the fact that weather models underestimate cloud cover during precipitation events, and this is shown in-depth in the case studies discussed in Section 11. The air temperature predictions tended to be too warm during shallow post frontal rain and snow events.
Fig. 10.41: Weighted average air temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during precipitation conditions only for the E-470 sites.

Fig. 10.42: Weighted average air temperature RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and during precipitation conditions only for Colorado plains sites.
Results Summary: There were not enough rain and snow cases to draw definitive conclusions about air temperature prediction error; however, there seems to be an indication that the surface air temperatures warm too quickly during rain and snow events over the High Plains of Colorado. This may be due to an underestimation of cloud cover by the models (too much direct solar radiation penetrating to the surface), which results in a warm bias.

Wind Speed Analysis

Wind speed prediction error was also examined when the observed wind speed was greater than 10 knots (5.1 m/s), which occurred in about 10-15% of the cases examined. For all three site categories (mountains, plains, and E-470 sites), there is an increase in error for all lead times during windy conditions. For E-470 (Fig. 10.43) the increase in error is on the order of 0.5–0.75 m/s and for the Colorado plains (Fig. 10.44) and mountains (Fig. 10.45), the increase is 1-2 m/s. The increase in errors for both E-470 and the Colorado plains sites seem to be fairly consistent through the day, but for the mountains there are slightly larger errors during the morning hours when the boundary layer was not well mixed.

These results indicate that, over all locations, the RWFS underestimates high wind speeds.

Fig. 10.43: Weighted average wind speed RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and the consensus forecasts during windy conditions only for the E-470 sites.
Fig. 10.44: Weighted average wind speed RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and the consensus forecasts during windy conditions only for the Colorado plains sites.

Fig. 10.45: Weighted average wind speed RMSE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) for all conditions (black line) and the consensus forecasts during windy conditions only for the Colorado mountain sites.
Results Summary: The RWFS underestimated the wind speeds during windy events. This is likely due to the model blending process that tends to smooth out extreme conditions. Techniques will be implemented for the winter of 2005-2006 that will improve the ability of the RWFS to respond to conditions that deviate significantly from average conditions.

10.3 Overall Performance of the Road Condition Treatment Module

10.3.1 Observed Road and Bridge Temperature Variance

Observed road and bridge temperatures vary greatly over short distances. This variability can be due to shading issues of permanent structures or even passing clouds on a partly cloudy day. In addition, differences in the make and model of road temperature sensors, how they were installed, and how they wear with age will impact temperature accuracy.

The spread of road and bridge temperature observations across the E-470 domain (47 miles of roadway) for three cases is shown in Figs. 10.46-10.51. The first case, from 26-30 November 2004 (Figs. 10.46-10.47), shows that, during peak heating, road and bridge temperatures vary by more than 5°C, both during scattered skies (26th) and overcast skies (27th), and by more than 10°C on a clear day (29th). Broken skies are observed on both 27 and 29 January 2005 between 09-12 UTC, but the road temperature sensor spread is vastly different between the two days with similar conditions. Even during times of relatively slow heating and cooling on a clear day, the road temperatures vary by up to 5°C, with even larger differences between the bridge temperature observations. This same spread among the observations is seen for 3-7 January 2005 (Figs. 10.48-10.49) under varying sky conditions. It appears that the observations are closest to each other during overcast situations; however, 13-17 February 2005 (Figs. 10.50-10.51) is a case where the observations are quite close across the E-470 domain throughout the complete range of sky conditions.

The observed differences have an impact on the forecast error statistics seen in the following sections, as it is difficult to establish ground truth.
Fig. 10.46: Road and bridge temperature observations for 7 RWIS sensors along E-470 for 26-28 November 2004.

Fig. 10.47: Road and bridge temperature observations for 7 RWIS sensors along E-470 for 28-30 November 2004.
Fig. 10.48: Road and bridge temperature observations for 7 RWIS sensors along E-470 for 3-5 January 2005.

Fig. 10.49: Road and bridge temperature observations for 7 RWIS sensors along E-470 for 5-7 January 2005.
Fig. 10.50: Road and bridge temperature observations for 7 RWIS sensors along E-470 for 13-15 February 2005.

Fig. 10.51: Road and bridge temperature observations for 7 RWIS sensors along E-470 for 15-17 February 2005.
Results Summary: There were large variations in observed road and bridge temperatures over a relatively small area (few 10s of miles). This result makes the prediction and verification of pavement temperature very challenging.

10.3.2 Overall Performance of the Road and Bridge Temperature Forecasts from the RCTM

This section examines the road and bridge temperature forecasts using recommended treatments as determined within the MDSS Road Condition and Treatment Module (RCTM). Measurement differences between the predictions and pavement sensors, expressed in median absolute error (MAE), were calculated. Bulk error statistics were computed and the average bias calculated (forecast minus observation) per lead time (out 48 hours) from 18 UTC RWFS output. There were a total of six road and two bridge temperature observation sites in the E-470 region, five road and two bridge temperature observation sites in the Colorado plains region, and five road and only one bridge temperature observation site in the Colorado mountain region (Vail Pass). Forecasts for the entire season (1 November 2004 to 15 April 2005) were used for the E-470 sites and from 1 February 2005 (when the CDOT RWIS first became available through MADIS) to 15 April 2005 for the Colorado plains and mountain sites.

The road temperature MAE for the E-470 sites ranges from around 1-1.5°C during the evening and overnight hours, but increases to a peak of about 3-4°C in the afternoon during the hours of maximum solar insolation (Fig. 10.52). When looking at the bias plots for this same parameter (Fig. 10.53), there is a noticeable cold bias that begins around 03 UTC (shortly after sunset) and reaches a peak around 15 UTC (around sunrise). After that time it decreases and has very little bias between 21 UTC and 03 UTC.

The MAE for the E-470 bridge sites (Fig. 10.54) has a diurnal pattern similar to that of the road temperature plot. The main difference between the two plots is that the magnitude of the first peak in the bridge temperature MAE is a bit higher. The second peak also rises earlier and decreases later in lead time so that the overall MAE is higher for bridge temperatures over road temperatures. Another thing to note in the bridge temperature plot is the notch that occurs around 24 hours out between 18-21 UTC. The two bridges along the E-470 highway run east-west with the temperature sensor along the southern edge of the bridge deck. During the afternoon hours, the bridge rail causes a shadow to form over the RWIS temperature sensor. The shadowing of the RWIS temperature sensor on the bridge contributes to the observed error, as the MDSS is predicting the surface temperature of the roadway assuming it is not in the shadow of the bridge railing.

There is a diurnal pattern to the bias plot that is positive from 21-06 UTC, with the peak around 00 UTC, and negative the rest of the time with a peak around 15 UTC. Around sunset the forecast bridge temperatures are too warm and around sunrise the bridge temperatures are too cold, suggesting that the forecasts are a bit delayed in response time during times of rapid change (10.55). Again, the shadowing of the RWIS sensors by the
bridge rails will contribute to the error and strong warm bias in the predictions during daylight hours. The cold bias at night suggests that the thermal properties of the bridge may need adjustment in the road temperature model.

Fig. 10.52: Average road temperature MAE computed from the 18 UTC forecasts from 1 November 2004 – 15 April 2005 for the E-470 sites. Local noon is at hour 0 and 24 as indicated.

Fig. 10.53: Average road temperature bias from the 18 UTC forecasts for 1 November 2004 – 15 April 2005 for the E-470 sites. Local noon is at hour 0 and 24.
Fig 10.54: Average bridge temperature MAE from the 18 UTC forecasts from 1 November 2004 – 15 April 2005 for the E-470 sites. Local noon is at hour 0 and 24.

Fig. 10.55: Average bridge temperature bias from the 18 UTC forecasts for 1 November 2004 – 15 April 2005 for the E-470 sites. Local noon is at hour 0 and 24.
For the Colorado plains sites, the road temperature prediction results are similar to the E-470 sites for MAE, except that the magnitude is again increased (Fig. 10.56). During the overnight hours the errors are around 2-2.5°C, while during the day the peak is closer to 4-5°C. There is also a slight cold bias during the day and a more significant cold bias at night for most of the lead times (Fig. 10.57).

As for CDOT bridge temperature predictions, the MAE ranges from about 1.5-2.5°C overnight and up to 6°C during the afternoon hours (Fig. 10.58). The bias, however, is largely negative much of the time with only a slight positive to more neutral during the early evening hours (Fig. 10.59).

The Colorado mountain site road temperature prediction errors are very similar to values for the plains (Fig. 10.60). The bias for road temperature goes positive in the afternoon and early evening hours, and is a higher magnitude than what is seen for the plains sites (Fig. 10.61).

For the bridge site (Vail Pass site only), the magnitudes again increase up to a peak of nearly 7°C in the afternoon hours (Fig. 10.62). The cold bias also matches the Colorado plains sites but to a greater magnitude of up to 6°C during mid-day (Fig. 10.63). CDOT indicated that the Vail pass bridge was not always treated and remained snow covered for large periods of time, sometimes days at a time; therefore, the error statistics must be viewed with extreme caution, as they are certainly impacted by the lack of adequate treatment. Shading from mountain peaks may also be an issue for both the road and bridge sites in the mountains, as evidenced by the notch in the MAE line during the afternoon hours.
Fig. 10.56: Average road temperature MAE, computed based on 18 UTC forecasts from 1 February 2005 – 15 April 2005 for the Colorado plains sites. Local noon is at hours 0 and 24.

Fig. 10.57: Average road temperature bias from the 18 UTC forecasts for 1 February 2005 – 15 April 2005 for the Colorado plains sites. Local noon is at hours 0 and 24.
Fig. 10.58: Average bridge temperature MAE from the 18 UTC forecasts from 1 February 2005 – 15 April 2005 for the Colorado plains sites. Local noon is at hours 0 and 24.

Fig. 10.59: Average bridge temperature bias from the 18 UTC forecasts for 1 February 2005 – 15 April 2005 for the Colorado plains sites. Local noon is at hours 0 and 24.
Fig. 10.60: Average road temperature MAE from the 18 UTC forecasts from 1 February 2005 – 15 April 2005 for the Colorado mountain sites. Local noon is at hours 0 and 24.

Fig. 10.61: Average road temperature bias from the 18 UTC forecasts for 1 February 2005 – 15 April 2005 for the Colorado mountain sites. Local noon is at hours 0 and 24.
Fig. 10.62: Average bridge temperature MAE from the 18 UTC forecasts from 1 February 2005 – 15 April 2005 for the Vail Pass site. Local noon is at hours 0 and 24.

Fig. 10.63: Average bridge temperature bias for the 18 UTC forecasts for 1 February 2005 – 15 April 2005 for the Vail Pass site. Local noon is at hours 0 and 24.
10.3.3 Verification of Daily Maximum and Minimum Road Temperatures

Forecast maximum and minimum road temperatures were examined in a similar way as was done for air temperature in Section 10.2.2. Maximum and minimum forecast values are derived from the 18 UTC hourly time series for each forecast site and stratified based on 0-23 hr (day one) and 24-47 hr (day two) forecasts. The entire season (from 1 November 2004 to 15 April 2005) was used for the E-470 sites, while 1 February 2005 to 15 April 2005 was used for the Colorado plains and mountain sites because the CDOT RWIS data was not coming in through the MADIS until late January 2005. The results are shown in Figures 10.58 through 10.63.

For daily maximum road temperatures, there are similar trends between the E-470 and Colorado plains sites, though there are far fewer points for the plains sites due to the shorter time period available (Figs. 10.64 and 10.66). Most of the forecasts are within +/- 6°C of the observations, and within that range more of the points are under-forecasting the road temperatures. Forecast values off by more than 6°C seem to have a tendency to over-forecast the road temperature, however. This suggests that the system is underestimating cloud cover. For the Colorado mountain sites, there is a great deal of scatter between the forecasts and observations (Fig. 10.68). Similar to the E-470 and plains regions, for errors above 10°C there seems to be a trend towards over-forecasting, but for smaller errors there is a fairly even spread of over- and under-forecasting of road temperatures. The under-forecasting of road temperature was also evident in the bias plots in Section 10.4.1 for E-470 and Colorado plains sites, while for the Colorado mountain sites, the bias plots indicated more of an over-forecast during the times of maximum road temperatures.

In all three regions there is a cold bias in the minimum road temperature forecasts (also seen in Section 10.9). Most of the forecasts are within 4°C for the E-470 sites and within 6°C for the Colorado plains and mountain sites (Figs. 10.65, 10.67, 10.69).

Overall, the RCTM appears to have a cold bias for road temperatures, especially for minimum road temperatures. These results may also reflect the fact that the system under-forecasts cloud cover, allowing road temperatures to increase during the day and decrease at night, when, in reality, the overcast conditions would actually prevent the road temperatures from warming up as much during the day and cooling off as much at night. Again, as was the case for air temperature, there is no increase in forecast error between day one and day two road temperature forecast values.
Fig. 10.64: Scatter plot of the forecasted maximum road temperature from the daily 18 UTC runs through the entire season, versus the observed maximum road temperature for the E-470 sites.

Fig. 10.65: Scatter plot of the forecasted minimum road temperature from the daily 18 UTC runs through the entire season, versus the observed minimum road temperature for the E-470 sites.
Fig. 10.66: Scatter plot of the forecasted maximum road temperature from the daily 18 UTC runs through the entire season, versus the observed maximum road temperature for the Colorado plains sites.

Fig. 10.67: Scatter plot of the forecasted minimum road temperature from the daily 18 UTC runs through the entire season, versus the observed minimum road temperature for the Colorado plains sites.
Fig. 10.68: Scatter plot of the forecasted maximum road temperature from the daily 18 UTC runs through the entire season, versus the observed maximum road temperature for the Colorado mountain sites.

Fig. 10.69: Scatter plot of the RCTM forecasted minimum road temperature from the daily 18 UTC runs through the entire season, versus the observed minimum road temperature for the Colorado mountain sites.
10.3.4 Performance Assessment Based on Conditional Road Temperature and Bridge Temperature Forecasts

Cold and Warm Conditions

As with air temperature, there are critical road temperature ranges that are most important for winter weather applications. This section describes how well the RCTM forecasts for road temperature and bridge temperature verified during certain weather conditions. For this analysis forecasts were stratified by road/bridge temperature between -2°C and 2°C (cold conditions – a critical range for freezing conditions), greater than or equal to 2°C (warm conditions), different percentages of cloud cover (cloud conditions), and the occurrence of rain and snow (precipitation conditions). Measurement differences between the predictions and pavement sensors, expressed in MAE, were calculated at times when only those conditions were observed, and conditional bias was also examined for cold and warm conditions. Since the sites used for road/bridge temperature observations (RWIS) do not report a full range of observations (such as cloud cover and precipitation), nearby ASOS sites were used to get the conditional observations.

The same set of forecasts that were used for the bulk statistics are used for this analysis. In addition to the conditional scores, all the plots show the MAE calculated over all forecast times (labeled no condition) as a baseline for comparison. The percentage of data used for the conditional MAE and bias calculations are indicated on the plots and labeled “total errors”. Note that for the Colorado plains and mountain sites some of the conditional statistics are not plotted due to a lack of observations.

During cold conditions, forecast errors for road temperature at the E-470 sites do not differ much from errors calculated for all forecasts (no conditions) except for spikes in the afternoon out past 24 hours that are 1-2°C higher (Fig. 10.70). The spikes occur at a time when the RWFS transitions the use of insolation from the MM5 and WRF models to the NWS models (Eta and WRF).

The increase in MAE for cold conditions at the bridges along E-470 is much higher during the afternoon hours for both the first 6 hours and out past 24 hours and is on the order of 4°C (Fig. 10.71). The bias plots for cold conditions for both road and bridge temperature forecasts at E-470 show a warm bias during the afternoon hours, changing to a cold bias for the overnight and morning hours (Figs. 10.72 and 10.73), with a higher magnitude of bias for the bridge temperature forecasts. The larger errors for the bridge sites are partly due to the shadowing of the pavement sensors during mid day as discussed earlier in this document.

The forecast errors for warm conditions are similar to the baseline errors for most lead times, with a slight increase in error during the morning hours. The road temperature bias during warm conditions is always cold for the E-470 sites, and for the bridge sites it is similar to the bias seen for the cold conditions, except the magnitude is less during the evening and more during the morning (Figs. 10.74 and 10.75).
Fig. 10.70: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cold and warm conditions for the E-470 sites.

Fig. 10.71: Average bridge temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cold and warm conditions for the E-470 sites.
Fig. 10.72: Average road temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cold conditions only for the E-470 sites.

Fig. 10.73: Average bridge temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cold conditions only for the E-470 sites.
Fig. 10.74: Average road temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during warm conditions only for the E-470 sites.

Fig. 10.75: Average bridge temperature bias from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during warm conditions only for the E-470 sites.
For the Colorado plains sites, the increase in the peak during the middle of the day for both road and bridge temperature forecast error is around 2-3°C in the first 6 hours and 3-6.5°C beyond 24 hours (Figs. 10.76 and 10.77). However, there are times, especially during the morning hours where there would potentially be more observations less than 2°C, when the cold condition errors are lower than the no condition errors for both the E-470 and Colorado plains sites. The bias plots for the Colorado plains sites show similar trends to what is seen for the E-470 sites with a slightly smaller cold bias at night (Fig. 10.78). For bridge temperatures, the negative bias at night and during the morning hours is again evident (Fig. 10.79). For the warm conditions, the road temperature bias is similar to the E-470 sites, but for bridge temperature, there is no warm bias during the evening and a larger cold bias in the morning as compared to E-470 sites (Figs. 10.80 and 10.81).

For the mountain sites, the increase in road temperature peak error during the day is significant beyond 24 hours and is on the order of 10°C (Fig. 10.82). It is apparent from the bias plots for road temperature that when cold road conditions exist there is a significant warm bias in the forecast during the heat of the day, and during warm conditions there is a slight cold bias at all times (Figs. 10.83-10.84). Shadowing of the pavement sensors in the mountains probably contributed to the differences between the forecasts and observations.

Fig. 10.76: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cold and warm conditions and warm for the Colorado plains sites.
Fig. 10.77: Average bridge temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cold and warm conditions for the Colorado plains sites.

Fig. 10.78: Average road temperature bias from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cold conditions for the Colorado plains sites.
Fig. 10.79: Average bridge temperature bias from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cold conditions for the Colorado plains sites.

Fig. 10.80: Average road temperature bias from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during warm conditions only for the Colorado plains sites.
Fig. 10.81: Average bridge temperature bias from the 18 UTC initialization forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during warm conditions for the Colorado plains sites.

Fig. 10.82: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cold and warm conditions for the Colorado mountain sites.
Fig. 10.83: Average road temperature bias from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cold conditions for the Colorado mountain sites.

Fig. 10.84: Average road temperature bias from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during warm conditions only for the Colorado mountain sites.
Cloudy and Clear Conditions

The cloud conditions were stratified by the observed cloud cover less than 20% (clear), 20%-50% (scattered), 50%-75% (broken), and greater than 75% (overcast).

For the E-470 sites, there is little difference in road temperature forecast skill under any one of the different cloud conditions (Fig. 10.85). Bridge temperature forecasts for E-470 become worse during the middle of the day with decreasing cloud cover (Fig. 10.86), which is expected given that the pavement sensors are shadowed by the bridge rails. Under clear conditions forecast errors increase by 3°C during the morning and afternoon. The observed saw-tooth pattern in MAE during the middle of the day is also likely due to the pavement sensor shading issue mentioned previously at the bridge sites.

For the Colorado plains sites, forecast errors for road temperature are larger during late morning hours when the cloud cover is less than 50% and at night when conditions are clear and there is more radiational cooling (Fig. 10.87). The increase in error is on the order of 0.5°C to 2°C. The bridge temperature MAE is similar to the road temperature MAE (Fig. 10.88).

For the mountain sites, there seems to be more variability in skill from one forecast lead time to the next for any one of the cloud conditions. There are also some notable differences during the middle of the day. Forecast errors for road temperature increase by 2°C when the observed cloud cover is less than 20% and decrease by 1°C to 2°C when the observed cloud cover is between 20%-75% (Fig. 10.89). Bridge temperature forecasts for the Vail Pass site are better when it is overcast and worse when it is clear (Fig. 10.90). These trends are most evident during the middle of the day with an increase in error of 1°C to 2°C for clear conditions and a decrease in error of 1°C to 4°C during overcast conditions.

Pavement sensor shading, pavement skin temperature measurement errors, the inability of weather models to accurately predict mixed sky conditions (cloudy, scattered, broken, etc.), and simplified assumptions about pavement characteristics in the pavement heat balance models all contribute to errors in predicting pavement temperature.
Fig. 10.85: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cloudy conditions for the E-470 sites.

Fig. 10.86: Average bridge temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during cloudy conditions for the E-470 sites.
Fig. 10.87: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cloudy conditions for the Colorado plains sites.

Fig. 10.88: Average bridge temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cloudy conditions for the Colorado plains sites.
Fig. 10.89: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cloudy conditions for the Colorado mountain sites.

Fig. 10.90: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 February 2005 – 15 April 2005) during cloudy conditions for the Colorado mountain sites.
Precipitation Periods

The conditional MAE values for the precipitation conditions were calculated for times when the closest ASOS reported rain or snow (E-470 only). The road and bridge temperature forecasts for the Colorado plains and mountain sites had such an extremely limited number of observations of these conditions (due to the fact that the road temperature observations were only available after 1 February 2005) that statistics were not computed for those sites. Road and bridge temperature forecasts for E-470 are slightly worse during the middle of the day when snow and rain are reported, with an increase in error of 1°C; the exception being for bridge temperature in the first 6 hours (Figs. 10.91 and 10.92).

Fig. 10.91: Average road temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during precipitation conditions for the E-470 sites.
Fig. 10.92: Average bridge temperature MAE from the 18 UTC forecasts for the entire demonstration season (1 November 2004 – 15 April 2005) during precipitation conditions for the E-470 sites.

Results Summary: The results from the road temperature analyses show larger differences between the observations and predictions during the middle of the day when solar effects are largest than at night. The differences are likely due to several factors including errors in measuring pavement skin temperatures by embedded sensors (e.g., pucks), limitations in the ability of weather models to predict insolation accurately, and limitations of the pavement heat balance model including simplified assumptions about pavement characteristics.

The bridge temperature analysis was compromised by several factors that included temperature sensors that were shadowed by bridge railings and, for the Vail Pass site, the realization that the bridge was not plowed routinely. The bias results do suggest that additional tuning of the bridge characteristics in the bridge temperature model may be required.

The results from the analyses performed during warm and cold periods, clear and cloudy periods, and precipitation periods indicate that several complex factors contribute to pavement prediction error. Predicted pavement temperatures were generally too warm during cold periods and too cold during warm periods. This may be due to the fact that the RWFS currently tends to damp out extremes during the production of the consensus weather forecast.
The pavement temperature predictions also tend to be too warm during periods of rain and snow. The warm air temperature bias likely contributes to these results as well as the fact that there seems to be too much direct insolation being predicted at the surface during precipitation periods.

All of these issues will be explored further prior to the winter 2005-2006 field demonstrations. System refinements will be implemented where applicable.

10.4 Distribution of Forecast Module Weights Used by the RWFS

As was described in Section 7, the RWFS is an ensemble forecast system that utilizes several different modules (models and data sets) to create a final consensus forecast. A component of its statistical processing includes a technique that weights the individual forecast modules based on its recent performance determined by comparing the location-specific forecasts with observations from the same sites. The components with the most skill (over the most recent 100 days) will have the highest weight.

A snapshot of how the weights were distributed at the end of the season for air temperature, dewpoint temperature, wind speed and cloud cover is examined for two sites: Denver International Airport (DIA), which is on the plains, and I-70 at Genesee which is in the foothills west of Denver. The plots show the final weight values per forecast lead time (out to 24 hours) from the 18 UTC run on 3 May 2005. It is important to note for all the plots that the saw-tooth pattern in some of the weight values is due to interpolation of 3 hr model data to 1 hr resolution. The non-interpolated forecast values tend to have more skill and thus more weight than the interpolated values. Also, the MAV-MOS (NWS MOS based on the Aviation Model) forecast was not interpolated to hourly resolution for the 2004-2005 field demonstration so there are no forecast values at the intermediate hours and thus that module gets no weight at those times.

Air Temperature

For air temperature at both DIA (Fig. 10.93) and Genesee (Fig. 10.94), the Eta model gets the most weight for a majority of forecast lead times. Secondary contributors differ somewhat between the two sites. For DIA, the MAV-MOS gets as much weight as the Eta model for many of the times when it provides a forecast, followed by the GFS. For the Genesee site secondary contributors come from the RUC model and the MAV-MOS. The weights are similar for the dewpoint temperature forecasts at both sites (Fig. 10.95 and 10.96); however, the RUC model is a primary contributor at DIA as well.
Fig. 10.93: Air temperature weight distributions for each of the individual model components per lead time as of May 3, 2005 for the Denver International Airport forecast site.

Fig. 10.94: Air temperature weight distributions for each of the individual model components per lead time as of May 3, 2005 for the Genesee, Colorado forecast site.
Fig. 10.95: Dewpoint temperature weight distributions for each of the individual model components per lead time as of May 3, 2005 for the Denver International Airport forecast site.

Fig. 10.96: Dewpoint temperature weight distributions for each of the individual model components per lead time as of May 3, 2005 for the Genesee, Colorado forecast site.
Wind Speed

For wind speed, the weights are more evenly distributed between the models and the distribution is different for each site. For DIA (Fig. 10.97), the Eta model and MAV-MOS ended up with slightly more weight than the other components for a majority of lead times followed by the WRF model in the first 10 hours, the MM5 model between 10 and 15 hours, and then the GFS model out to 24 hours. For Genesee (Fig. 10.98), the Eta model gets high weight in the first few forecast hours and then quickly drops down, and then the GFS and RUC models get the most weight. At the middle lead times, the WRF model gets a majority of the weight and then the Eta, GFS, and RUC models get the most weight out to the end of the 24 hr period.

It is interesting to note that the mesoscale models (MM5 and WRF) do not contribute very much to temperature and dewpoint at either site, but they do for wind speed. Cloud-cover weights, which are only shown for the DIA site (Fig. 10.99), are dominated by the GFS, Eta, and MAV-MOS (at times when it provides a forecast), with little contribution from the other models.

Fig. 10.97: Wind speed weight distributions for each of the individual model components per lead time as of May 3, 2005 for the Denver International Airport forecast site.
Fig. 10.98: Wind speed weight distributions for each of the individual model components per lead time as of May 3, 2005 for the Genesee, Colorado forecast site.

Fig. 10.99: Cloud cover weight distributions for each of the individual model components per lead time as of May 3, 2005 for the Denver International Airport forecast site.
Analysis of the weights for several different parameters shows that there is a large variation in forecast skill between the models for different variables, at different lead times, and at different locations. This supports the idea that an ensemble forecast provides a better overall forecast than any one model. There is a limitation to the ensemble approach. If each input module gets some weight and none of them outperform the others most of the time, the output will generally be an (weighted) average of the members. This will end up smoothing out extremes, which can reduce the forecast skill during periods of rapid transitions.

**Results Summary**: The final distribution of weights associated with each RWFS forecast module for the verifiable parameters (air and dew point temperature, wind speed, and cloud cover) indicates that the statistical corrections (dynamic MOS) applied to the NWS models (Eta and GFS) had the most skill overall. The mesoscale models (MM5 and WRF) did not perform as well, which is a finding consistent with the results shown in Section 10.2. The limitation of the NWS models for road weather forecasting is their 3-hr temporal resolution.

### 10.5 Quantitative Precipitation Forecasts (QPF) Data

The concept behind the RWFS is based on having good observations near the forecast points that feed back into the system and tune each forecast parameter dynamically in order to optimize the contributions of each model in the ensemble on a run to run basis. However, forecasting any characteristic of precipitation (i.e. timing, rate, and phase) is very difficult in part due to problems in the forecasting process (model physics and knowing the state of the atmosphere) and also due to the poor observation network and the inability to verify actual precipitation amounts, particularly for winter precipitation (e.g., snow, sleet, etc.).

The lack of quality real-time winter precipitation observations prevents the RWFS from tuning itself for the QPF parameter\(^2\). Without quality, real-time quantitative precipitation observations (liquid equivalent), the RWFS quantitative precipitation prediction modules would end up at best, being averaged (10-member average), and at worst, being tuned incorrectly due to poor observation quality.

Due to this fact, it was necessary to modify the RWFS to fix the QPF weights across the ten modules based on expert opinion. The weights remained the same as what was used in the 2003-2004 field demonstration in Iowa. The weights for the QPF parameters are shown in Table 10.1.

\(^2\) The lack of high quality, real-time quantitative precipitation information is a nationwide problem, and not just limited to Colorado.
Table 10.1. Weights given to each of the ten RWFS quantitative precipitation forecast modules.

<table>
<thead>
<tr>
<th>Des Moines &amp; Ames Area RWFS QPF Weights</th>
<th>Forecast Period</th>
<th>GFS 2 hr</th>
<th>Eta 3 hr</th>
<th>MM5 2 hr</th>
<th>MM5 3 hr</th>
<th>MM5 4 hr</th>
<th>WRF 2 hr</th>
<th>WRF 3 hr</th>
<th>WRF 4 hr</th>
<th>Total MM5</th>
<th>WRF RUC</th>
<th>MAV-MOS</th>
<th>Total %</th>
<th>TOTAL MM5+WRF Contribution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 hr Forecast</td>
<td></td>
<td>9</td>
<td>11</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>37</td>
<td>17</td>
<td>14</td>
<td>12</td>
<td>43</td>
<td>0</td>
<td>0</td>
<td>100.00</td>
</tr>
<tr>
<td>3 hr Forecast</td>
<td></td>
<td>9</td>
<td>11</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>37</td>
<td>17</td>
<td>14</td>
<td>12</td>
<td>43</td>
<td>0</td>
<td>0</td>
<td>100.00</td>
</tr>
<tr>
<td>6 hr Forecast</td>
<td></td>
<td>9</td>
<td>11</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>37</td>
<td>17</td>
<td>14</td>
<td>12</td>
<td>43</td>
<td>0</td>
<td>0</td>
<td>100.00</td>
</tr>
</tbody>
</table>

The subjective opinion prior to the field demonstration was that the time-lagged ensemble of mesoscale models (WRF and MM5), which were being run hourly out to 18 and 24 hours respectively, would have a better handle on precipitation timing and amount. In addition, because of the “hot start” process, it was felt that the models did a better job of predicting very light precipitation cases. As can be seen above, the WRF and MM5 data were given 80% of the total weight for QPF in the RWFS.

Several cases studies were performed to compare the individual model QPF to the actual liquid-equivalent precipitation collected by a GEONOR precipitation gauge that was installed at Denver International Airport by NCAR for a Federal Aviation Administration project. The results of these case studies can be found in Section 11.

**Recommendation:** The ability of models to predict precipitation start and stop time and amount varies greatly between models. If a data fusion system that adjusts itself based on observations similar to the RWFS is utilized, care must be taken to ensure that the weights given to individual prediction modules are appropriate. If only low quality verification data are available, the weights should be fixed based on experience and/or expert opinion.

### 10.6 Insolation Data

It is well recognized that incoming solar radiation (insolation) is a critical parameter for predicting road temperature and thus very important in the RWFS process. Short wave radiation data were available from the MM5, WRF, Eta, and GFS models, but there were significant differences in the way they were calculated and provided. For example, the GFS short wave radiation field is a 3-hr time-averaged value, while the Eta provides an instantaneous value. Listed below are descriptions of the issues that arose with the short wave radiation fields used in the MDSS.
**Eta Model:** The short wave radiation data from the Eta model is an instantaneous value. Hourly output of the Eta insolation data are not available, reducing the utility of these data.

**GFS Model:** The short wave radiation data from the GFS model is a time-averaged value over a 3 hr period. Because of the time averaging characteristic, it is not practical to use it as an input to a road temperature model.

**WRF and MM5 Models:** The radiation data from the WRF and MM5 models provide instantaneous values and have an hourly temporal resolution.

The MDSS was configured to utilized insolation data (short and long wave) from the MM5 and WRF models. Not only did the MM5 and WRF generate insolation data with attractive characteristics (hourly and instantaneous values), these two models were heavily weighted in the calculation of QPF, therefore providing some consistency between precipitation amounts and insolation.

Because of the nature of real-time shortwave radiation measurements whereby values can change dramatically over short time periods (e.g., during partly cloudy conditions) and because real-time insolation measurements are not broadly available, it is not practical to use these data to forward correct the RWFS insolation forecasts; therefore, the weight blending values for insolation had to be fixed. At the beginning of the season, the RWFS was configured to use the MM5 insolation forecasts for near term forecasts (0-15 hr) and Eta insolation forecasts for the longer term forecasts (15-48 hr). The blending was later changed for reasons described below.

Two pyranometers, one located at the Marshall test field site (about 5 miles south of Boulder, Colorado) and the other located at an RWIS station at E-470 and 6th Parkway (about 5 miles south of DIA), which were about 30 miles apart, were compared to find out how the observations changed over that distance. It became apparent that on completely clear days the Vaisala pyranometer located at the RWIS site was consistently lower than the observations from the Marshall pyranometer. Vaisala was contacted and they did find a problem with local site scaling factors, which had reverted back to some default due to a power failure. This problem was not corrected until 20 May 2005; therefore, data from the Marshall pyranometer was used to evaluate the output from the MM5 and WRF models.

The insolation (short wave radiation) values from each individual model compared with the pyranometer measurements from the Marshall site for an 11 day period is provided in Fig. 10.100. During this period, there were five clear days (31 January – 4 February 2005) where the insolation values were near the theoretical maximum for this latitude and longitude (~630 watts per square meter), several partly cloudy days on either side of the clear days, and two overcast days (7 – 8 February 2005) at the end of the period examined.
Incoming SW Radiation

Fig. 10.100. Comparison between the Marshall, Colorado pyranometer observations (black solid line) and the Eta (red circles), GFS (orange triangles), MM5 (green diamonds), and WRF (blue squares) shortwave radiation forecasts.

This comparison illustrates the differences between models and their respective physics for determining cloud characteristics. For example, MM5 performed a bit better on partly cloudy days while WRF tended to be closer on overcast days during this time period. Also, Eta was closer to MM5 than to WRF.

Preliminary verification work performed in February 2005 showed that on any given day the WRF model did just as well as the MM5 for insolation forecasts and either one had an equal chance to outperform the other. On 1 March 2005, the weights were changed to have an equal 50% blend of the WRF and MM5 insolation values. The result of this blending is shown in Fig. 10.101.
The blending used by the RWFS provided the best overall results even though the weights were fixed.

**Results and Recommendations:** The ability of models to predict insolation varies greatly between models, particularly in partly cloudy conditions. Care must be taken to ensure the model values compare well with measured values. Because insolation measurements are critical for road temperature prediction, it is recommended that insolation measurements be added to surface observing stations and be available in real time. Real-time access to insolation data would provide an opportunity for systems like the RWFS to utilize the data and optimize predictions.

### 10.7 Bridge Frost Potential Product

A bridge frost potential algorithm was developed and implemented within the MDSS for the 2004-2005 field demonstration as described in Section 9. Verification of this algorithm was complicated by the fact that because of Colorado’s dry conditions, road and bridge frost is rare. In addition, residual chemicals on the pavement made it difficult to confirm that bridge frost occurred, and there were no dedicated sensors or observations dedicated to collect road and bridge frost data. Even with these constraints, an attempt
was made to verify the proper operation of the algorithm using two cases where roadside frost was manually observed.

A member of the MDSS development team made two trips over the E-470 bridge that crosses the Platte River (Platte Valley bridge). On 7 January 2005, bridge and roadside (on the guardrails, shoulder, and vegetation) frost was present just after dusk (~5 PM LT). On 1 February 2005, light ground frost was present but no bridge frost was evident when inspected just before dawn (~7 AM LST).

For the 7 January 2005 case, a forecast run time of 00 UTC was analyzed. According to the RWIS site observations located at the Platte Valley bridge, the pavement temperature (dashed black line in Fig 10.102) dropped below the dewpoint temperature (solid black line) around 03 UTC. Frost deposition should take place when the pavement temperature falls below the dewpoint temperature (at temperatures below the freezing mark)\(^3\). Assuming no winter maintenance treatments were performed, frost will then continue to be present until the road temperature warms up above 0°C and melts the frost. For this case the observations indicate that frost was likely to begin forming just after dusk at around 02 UTC, which was confirmed at approximately the same time. The frost should have lasted until approximately 17 UTC with no treatment.

The road temperature forecast (dashed red line in Fig. 10.102) from the RCTM is quite close to the actual observations throughout the period; however, the dewpoint temperature forecast (solid red line) is too high (too moist) between 05-13 UTC. The predicted road temperature forecast is lower than the predicted dewpoint temperature forecast and, as designed, the algorithm indicates a potential for frost formation by about 01 UTC. The timing of the frost potential alert is slightly earlier. This is because a Monty-Carlo approach is applied which takes a range of air, dew point, and pavement temperatures above and below the forecast value to account for the uncertainty in predicting these parameters. The forecasted frost alert level is initially marginal, but worsens to poor and then extreme conditions by 04 UTC due to the prolonged state of optimal frost deposition conditions. The alerts continue to be labeled extreme until the road temperature crosses the 0°C line around 17 UTC. The frost potential forecast for this case was very good in timing, despite a poor dewpoint temperature forecast.

\(^3\) Technically, frost deposition will begin to take place when the pavement temperature is below freezing and also below the frost point temperature.
Fig. 10.102: Frost potential algorithm output for 00 UTC 7 January 2005. The solid black line is the dewpoint temperature observation and the dewpoint prediction is the solid red line. The pavement (bridge) temperature observation is the black dashed line and the forecasted pavement (bridge) temperature is the dashed red line. The frost potential alert levels are indicated by the colored dots along the bottom with green=ok, yellow=marginal, red=poor, and magenta=extreme. The black dots represent times when the pavement temperature observations fell below the dewpoint temperature observations indicating the likelihood of frost deposition on the pavement.

On 1 February 2005, visual confirmation was made that there was light ground frost in the low lying areas of the Platte River Valley, but none on the bridge deck surface itself, possibly indicating marginal potential for bridge frost to occur. For the 00 UTC MDSS run (Fig. 10.103), it is seen that in fact the road temperature observations never fell below the dewpoint temperature observations, confirming that no bridge frost should have formed.

The dewpoint temperature forecast for this case is quite good through 16 UTC, but the road temperature forecast is about 2 to 3°C too cold. This cold bias causes the road temperature forecast to drop below the dewpoint temperature forecast around 10 UTC and triggers a marginal bridge frost potential alert from 08-10 UTC. According to the forecast, the frost potential goes to poor around 11 UTC and then to extreme at 13 UTC. The road temperature forecast increases above 0°C around 16 UTC, at which time the frost alerts end. For this case a forecast of marginal frost potential would have been sufficient given the actual conditions.
**Fig. 10.103:** Frost potential algorithm output for the 00 UTC 1 February 2005 run. The solid black line represents the dewpoint temperature observation and the dewpoint prediction is the solid red line. The pavement (bridge) temperature observation represents the black dashed line and the forecasted pavement (bridge) temperature is indicated by the dashed red line. The frost potential alert levels are indicated by the colored dots along the bottom with green=ok, yellow=marginal, red=poor, and magenta=extreme. The black dots represent times when the pavement temperature observations fell below the dewpoint temperature observations indicating the likelihood of frost deposition on the pavement.

**Results Summary:** Because of the lack of adequate verification data and analyzed cases, it is not possible to draw conclusions on the bridge frost potential product. The limited results provided herein are encouraging, but additional testing and analysis is required.

**11 SELECTED CASE STUDIES**

While bulk statistics provide a useful assessment of the overall quality of RWFS and pavement temperature forecasts, it is also quite valuable to do an in-depth examination of data quality for a variety of weather events. Such case studies help to reveal the reasons behind forecast errors made apparent in the bulk statistics. It is also possible to determine a scale of errors that is reasonable to expect under the circumstances most important to
users – when the roads are being impacted by winter weather. Four case studies were chosen for this analysis.

These cases were chosen to include a variety of winter weather scenarios that occurred in the Denver area during the winter 2004-2005 demonstration. Verification of forecasts generated from the RWFS for DIA were chosen because of the high quality verification data available at DIA. The results of these analyses should be applicable to the E-470 and Denver area CDOT sites.

The case studies for the 2004-2005 winter season include the following events:

- **Moderate Snow Case**  27-29 November 2004
- **Light Snow Case**   12 January 2005
- **Warm, Moderate Snow Case**     13 March 2005
- **Warm, Heavy Snow Case**  9-11 April 2005

11.1 Verification Methods

Verification data used for the case studies included ASOS stations located at the Denver International Airport (DEN) and six RWIS sites along the E-470 roadway. A GEONOR precipitation gauge is also located at the Denver International Airport (DIA) as part of an FAA sponsored project called the Weather Support to Deicing Decision Making (WSSDM) (Rasmussen, et. al., 2001). This precipitation gauge had a Double Fence Intercomparison Reference (DFIR) shield surrounding it in order to minimize the affects of the wind. A photo of the DFIR wind shield surrounding the GEONOR gauge at DIA is provided in Appendix C. According to Rasmussen, et al. (2001), this snow gauge and wind shield combination measures within 5% of manual (ground truth) observations. A higher confidence is placed in the accuracy of the GEONOR liquid equivalent precipitation measurements then the hourly automated precipitation measurements made at ASOS sites.

11.2 Case Studies

11.2.1 November 27-29, 2004

The first significant snow storm to hit the Denver metro area occurred over Thanksgiving weekend, one of the busiest travel weekends of the year. The snow began around 02 UTC on 28 November 2004. There was approximately 1 inch of accumulation and then there was a lull in the storm from 05-14 UTC. The snow started falling again at 14 UTC and continued all day and into the next, through 15 UTC on 29 November. A total of 5-8 inches of snow fell in the area by the end of the event.

For this event, three runs, each out 24 hours, from the RWFS are examined and compared for all the meteorological state parameters, including air temperature, dewpoint
temperature, wind speed, and cloud cover, as well as quantitative precipitation forecast (QPF).

The first run from 18 UTC on 27 November 2004 is examined to address how the individual models predict the approach of the storm and the start of the precipitation. The next run is from 12 UTC on the 28th which shows how the system did during the heart of the storm. The final run starts at 06 UTC on the 29th to look at how the end of the event was forecast, especially with regard to the precipitation end time.

**Air Temperature**

Forecasts from each of the ten RWFS input modules (see Section 10.1) show a very large spread in the predicted air temperature for the entire time 48 hr period (Fig. 11.1). The models are as far apart as 6°C at times. The mesoscale models (MM5 and WRF) start too warm, while the Eta is too cold. The GFS starts out fairly close but gets much too warm a few hours later when it fails to forecast the frontal passage. The final RWFS forecast is within 1°C of the observations for much of the time, with a maximum difference of 1.5°C for a short period. The frontal passage is forecast by all the models to come through the area at 00 UTC on 28 November, which was a few hours earlier than observed. This also corresponds to the time of the maximum temperature difference between the RWFS and the Denver ASOS. Between the initial onset of snowfall and the second, longer-lived snow period (as seen in the next run), the models have significant differences among their air temperature forecasts. In spite of the conflicting forecasts, the ensemble approach with the weighting function of the models results in a good consensus forecast overall and this continues through the first 24 hours.

![Fig. 11.1: 18 UTC 27 November 2004 RWFS run showing an air temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.](image-url)
When looking at the 12 UTC run from 28 November (Fig. 11.2), all of the models except the Eta warm the air during the afternoon hours whereas the observed air temperature steadily decreases throughout the day. This over-forecast of air temperatures causes the RWFS to be about 2°C off during the afternoon and evening hours and then it catches up again around midnight and is within 1°C through the end of the run. Again, the majority of the weather forecast models performed poorly for air temperature.

![Air temperature comparison graph](image)

**Fig. 11.2:** 12 UTC 28 November 2004 RWFS run showing an air temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

The 06 UTC system run from 29 November (Fig. 11.3) shows better agreement with the observations until the end of the period. The RWFS air temperature is within about 0.5°C until about 00 UTC on the 30th. The errors increase again during the evening and overnight hours due to a great deal of spread between the models, which were all too warm.
Fig. 11.3: 06 UTC 29 November 2004 RWFS run showing an air temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

**Dewpoint Temperature**

An incredibly large spread in dewpoint temperature between the models is apparent in the comparisons for both the 18 UTC on the 27th and 12 UTC and the 28th runs (Figs. 11.4 and 11.5). For the first run, the MM5 performs fairly well, while during the second run the GFS is the closest. Again, in spite of the large differences between the models, the RWFS final consensus forecast is within 1-1.5°C most of the time for both runs.

For the third run examined (Fig. 11.6), the NCEP models (GFS and Eta) perform better early on and then the mesoscale models do better later in the time series. The RWFS dewpoint temperature forecast for this run is very good through the end of the snow event.
Fig. 11.4: 18 UTC 27 November 2004 RWFS run showing a dewpoint temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Fig. 11.5: 12 UTC 28 November 2004 RWFS run showing a dewpoint temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.
Wind Speed

The wind speed forecasts from the entire forecast module suite for the 18 UTC 27 November run (Fig. 11.7) started out about 5 m/s too low; however, the forward error correction scheme (FEC) applied within the RWFS increased winds in the consensus forecast so it compared quite closely to the observations. After the frontal passage (~22 UTC), forecast wind speeds from all of the models and the consensus were consistently low compared to the observations through the end of the first run and through 00 UTC on 29 November, as shown in Fig. 11.8. After that time, the wind speed decreased and all the forecast models are much more in line with the observations during the middle and end of the snowfall period as shown in Fig. 11.9. However, after the snow ended the winds became calm while the models predicted the winds to continue.
Fig. 11.7: 18 UTC 27 November 2004 RWFS run showing a wind speed (m/s) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Fig. 11.8: 12 UTC 28 November 2004 RWFS run showing a wind speed (m/s) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.
Cloud Cover

All of the models appear to have difficulty forecasting complete overcast (100% sky cover) and completely clear (0% sky cover) conditions. For this case, all of the models predicted conditions closer to broken skies when completely overcast skies were observed (Fig. 11.10).

At the start of the 12 UTC run on 28 November (Fig. 11.11), some of the models forecasted scattered cloud cover during completely cloudy conditions. The models were allowing more solar radiation to penetrate the clouds than was actually occurring, impacting air temperature forecasts, which were too high during the afternoon of the 28 November as illustrated in Fig. 11.2. Toward the end of the snow event (end of the 12 UTC 28th and beginning of the 06 UTC 29th (Fig. 11.12) runs, the models do creep up towards overcast conditions, but they never reach 100%. For the 06 UTC 29th run, the final RWFS consensus forecast starts out at 100% overcast because the FEC process was applied and remains there near 100% for five hours. By the end of the period, the observations have quickly dropped to clear, whereby the models are slow to respond and change only to scattered sky conditions.
Fig. 11.10: 18 UTC 27 November 2004 RWFS run showing a cloud cover time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Fig. 11.11: 12 UTC 28 November 2004 RWFS run showing a cloud cover time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.
Fig. 11.12: 06 UTC 29 November 2004 RWFS run showing a cloud cover time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Quantitative Precipitation Forecasts (QPF)

Within the RWFS there are set thresholds for hourly probability of precipitation (POP) and quantitative precipitation forecast (QPF) values that must be met before precipitation will be declared by the system. For the 2004-2005 winter field demonstration the POP threshold was set at 25% while the QPF threshold was 0.05 mm/hr.

As previously mentioned, the start time of this event was about 02 UTC on 28 November 2004 as indicated by the DIA GEONOR precipitation gauge observation (black line in Fig. 11.13). The models differed on the start time, most of which were earlier than actual and a few missed the initial very light snow event altogether and just forecasted the start of the heavier snowfall that began about 8 hours later. It is interesting to notice that the older mesoscale models (MM5_3, MM5_4, WRF_3, and WRF_4) actually do better than the latest runs for the start time of the first light event. The Eta also did very well on the earlier start time. The RWFS consensus forecast (red line) predicted the start time of the first very light event about two hours early. The forecast rate of snowfall was fairly close to the actual; however, because the consensus RWFS forecast had the break in the snowfall forecast later than observed, the predicted amounts at the end of the time series were high by approximately 0.03 inches.

At the end of the first time series, the RWFS has snow beginning again around 16 UTC when the observations show it started two hours earlier. In the 12 UTC 28th run (Fig.
the Eta and GFS models had a start time of 12 UTC; however, the mesoscale models all delayed the snow until much later. The RWFS did not meet the threshold for declaring precipitation until 00 UTC on the 29th, approximately 9 hours late. If there were no POP and QPF threshold requirements (pink line), the start time would have been better, starting at 16 UTC; however, the snow rate would have still have been much too low.

The final run from 06 UTC 29th (Fig. 11.15), shows the RWFS forecast tracking below the GEONOR precipitation observations. The RWFS then predicts a break in the snowfall at 11 UTC, which was actually observed at 14 UTC. This break lasts only a few hours, while the RWFS had it lasting six hours. The short-lived snow shower that moved through at 17 UTC was forecast by the WRF and final consensus forecast. If no thresholds had to be met in order to declare precipitation for this run, the RWFS would have been closer to the actual observations for this event.

*Fig. 11.13: 18 UTC 27 November 2004 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.*
Fig. 11.14: 12 UTC 28 November 2004 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.

Fig. 11.15: 06 UTC 29 November 2004 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.
11.2.2 January 12, 2005

Air Temperature

A light snow event moved across the E-470 demonstration domain from 11 UTC – 18 UTC on 12 January 2005. At the beginning of the event, there was also freezing rain reported for about 20 minutes at the Denver ASOS site. For the 06 UTC 12 January 2005 run examined here, the RWFS declared the precipitation type as snow for the event.

For this case, the models were split high and low around the air temperature observations at the start of the time series and into the beginning of event (Fig. 11.16). The GFS and WRF were too warm, while the Eta and MM5 started out close, but then became too cold. The RUC was not available for any parameters for this run. Towards the end of the snowfall, all of the models warmed the air up quickly during the afternoon hours when in reality it did not warm up much at all during that time. Around 00 UTC the models came back in line with the observations for awhile, but did not drop off enough into the overnight hours at the end of the time series.

![Graph showing air temperature comparison](image)

Fig. 11.16: 06 UTC 12 January 2005 RWFS run showing an air temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Dewpoint Temperature

Saturated conditions (100% relative humidity) were not forecasted for this case by any of the models as seen by the dewpoint temperature forecasts, which were much too low throughout the period (Fig. 11.17). The final RWFS consensus forecast was off by 4°C for most of the lead times as it was tracking the majority of models. For this run, the
GFS and Eta outperformed the mesoscale models, though they were still 2-3°C off at times.

Fig. 11.17: 06 UTC 12 January 2005 RWFS run showing a dew point temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Wind Speed

At the start of the time series and into the beginning of the event, the wind was calm and then it quickly jumped up to 9 m/s at 15 UTC (Fig. 11.18). The observations were fairly noisy (high to low wind speeds) during the entire period. The model forecasts were similar to one another and did not catch the wind speed peaks. The RWFS final forecast started out calm due to the FEC and then steadily increased during the next few hours. During the second half of the period, while the observations were fluctuating, the RWFS did a good job on the trends; it was just unable to pick up on the maximum and minimum spikes.
Fig. 11.18: 06 UTC 12 January 2005 RWFS run showing a wind speed (m/s) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Cloud Cover

Once again, the cloud cover forecasts from all the models seem to be problematic. At the start of the time series, the mesoscale models were predicting scattered skies while the Eta and GFS were forecasting broken skies (Fig. 11.19). The observations show completely overcast skies. FEC helps the RWFS accurately forecast the overcast conditions at the beginning of the time series. The models do increase cloud cover towards overcast at the start of the event, but were several hours late. The most recent mesoscale models did the best job at the beginning of the snow event, but decreased the cloud cover too early at the end of the event. A few hours after the snow began, the models are in fairly good agreement with the observations, but as skies become clear, the models and final consensus forecast kept scattered clouds through the end of the time series.
Quantitative Precipitation Forecasts (QPF)

Even with the dry bias in the forecasted dewpoint temperatures and cloud cover at the beginning of the event, the start time of the precipitation forecast was quite good (Fig. 11.20). There was consistency between nearly all the models on the start time, though the total liquid equivalent accumulation varied from 0.15 to 0.33 inches. The most recent WRF model matched the total accumulation and the GFS was also very close. The two latest MM5 runs were just a bit low, while the oldest run was too high. The final RWFS consensus forecast was excellent for the start time and just 0.01 inches low on the total amount. The end time was also quite good as it was within 1 hour of the actual end time. If no threshold had been applied in the RWFS to declare precipitation, the start time would have been a few hours too early, but the total amount would have been right on. Overall, this was a great QPF forecast by all the models and the RWFS for the precipitation timing, as well as the total amount.
Fig. 11.20: 06 UTC 12 January 2005 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.

11.2.3 March 13, 2005

A moderate snow event moved over the E-470 corridor on 13 March 2005 and dropped 4-6 inches of snow. The 00 UTC RWFS run from 13 March 2005 captured both the start and end of the event and is examined here.

Air Temperature

The evening before the start of the snow, the air temperature was a warm 11°C (Fig. 11.21). Approximately five hours later (~03 UTC), the front passed and the air temperature dropped significantly to -2°C. At this time, however, the closest air temperature forecast by any of the models was still about 5°C too high and the worst forecasts were off by nearly 10°C. Even though the RWFS had an air temperature forecast of 3°C at the start of the event, it still declared the precipitation type to be snow. Several hours into the event the models finally converged and were nearly all within 2°C of the observation, with the RWFS giving an excellent forecast through the end of the event.
Fig. 11.21: 00 UTC 13 March 2005 RWFS run showing an air temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

**Dew Point Temperature**

For the dewpoint temperature (Fig. 11.22), the GFS and Eta started out much too dry, but the MM5 and RUC models were closer. The observations fell sharply with the passage of the front just before the start of the event, but then quickly rose again when the snow started. The MM5 had a good forecast during the entire event, while the Eta performed well for the second half of the event. The RUC was much too dry throughout the snow event. In this case, with quite a bit of spread between models, the RWFS consensus forecast was too low throughout most of the forecast period.
Fig. 11.22: 00 UTC 13 March 2005 RWFS run showing a dewpoint temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

**Wind Speed**

The models appear to have a low bias in the wind speed forecasts during times of speed greater than 6 m/s for the entire event (Fig. 11.23). The MM5 and WRF have higher peaks, but the final consensus forecast appears much more damped overall. Because of its blending technique, the RWFS is unable to pick up short-lived peaks and lulls in wind speed, particularly when the models do not capture this characteristic.
Fig. 11.23: 00 UTC 13 March 2005 RWFS run showing a wind speed (m/s) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

**Cloud Cover**

Just as for the previous cases shown, the cloud cover forecast does not capture completely cloudy conditions very well (Fig. 11.24). All of the models under-forecasted cloud cover at the start of the event with the oldest MM5 and WRF being the worst. The models do better during the middle of the event, with many forecasting very near 100%, particularly the WRF model. The RWFS final forecast does increase at the start of the period; however, it is too gradual and does not approach overcast until 3-4 hours after the snow began. After the snow ended, the cloud cover does not dissipate quickly, so the models are able to capture the situation better.
Quantitative Precipitation Forecasts (QPF)

According to the GEONOR precipitation measurements at DIA, the snow started around 5 UTC (Fig. 11.25). The GFS was too early; however, most of the other models and the consensus forecast all agreed on a start time around 7 UTC, with a few MM5 and the latest WRF runs showing an hour or two later. The snow ended just after 15 UTC, but the RWFS showed it continuing until 20 UTC, mainly due to the MM5 forecasts for continued snow. The forecast snow rate from the RWFS was good, and because the late start and stop times balanced each other out, the total accumulation forecast was consistent with the observations. For this run, there was no significant difference between the RWFS forecast with and without the precipitation thresholds.
11.2.4 April 9-11, 2005

The biggest snow storm of the season along the Front Range of Colorado occurred on 10-11 April 2005. There was a total of 10–20” of snow along E-470 with 15-25” along the southern Denver CDOT routes and 20-30” across the western Denver CDOT routes. Because this was a long-lived event, two different MDSS runs are examined here; 00 UTC 10 April 2005 to cover the start of the event and 18 UTC 10 April 2005 to cover the end of the event.

Air Temperature

Because this was a typical spring storm for Colorado, the air temperature was very high early on in the event; 12ºC at 00 UTC on 10 April (Fig. 11.26). At the start of the period, there was good agreement between the models, though the forecasts are all about 4ºC too warm, with the exception being the GFS, which was too cold by 1.5ºC. The RWFS forecast matched the observation. At the beginning of the snow event, the RUC was much too high, but all the other models agreed. The final forecast was quite close to the observations, and this was crucial for getting the precipitation phase correct. Around 10 UTC, the WRF model was close; however, the other models were too warm, driving the RWFS to be about 2ºC too warm.
A dramatic change for the worse occurred in the next sequence of model runs. When evaluating the 18 UTC MDSS run which covered the middle of the event (Fig. 11.27), the models had significant trouble with the air temperature forecasts. The observations remained at or just below the freezing mark and it continued to snow, while the RWFS consensus forecast was pulled up above 0°C by all the models. As a result, rain was predicted for part of the time. Toward the end of the event, some of the model forecasts dropped below the observations, and the consensus forecast actually became much closer to the observations through the end of the time series.

![Time-series plot of air temperature](image)

**Fig. 11.26:** 00 UTC 10 April 2005 RWFS run showing an air temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.
Dew Point Temperature

For the start of the 00 UTC time series, all the models, except the GFS, were much too dry with regards to the dewpoint temperature forecasts (Fig. 11.28). The FEC method improved the initial RWFS forecast, but over the next couple of hours, the forecast was influenced by the GFS model, which caused it to be slightly too moist. At 03 UTC, the RWFS dewpoint fell and fluctuated throughout the period. As discussed earlier, this sawtooth pattern is due to the MAV-MOS model component (not shown here) having 3 hourly forecast values that are not interpolated to hourly output. The MOS forecast received a great deal of weight for this event and actually pulled the RWFS final forecast down from the observations while the other models were forecasting higher dewpoints. At the start of the event, the dewpoint forecasts were too low by 2–3°C and then low by 4–5°C when the MOS forecast pulled it down. During the snow event the forecasts agree well with the observations except, again, at times when the MAV-MOS had an influence.

For the 18 UTC run, the consensus forecast has the same pattern as the 00 UTC run where it was too moist for a few hours early, and then dry later on (Fig. 11.29). The forecasts from all the models, as well as the RWFS, had a dry bias through the rest of the event, continuing to decrease the dewpoint temperature gradually. After the event, the air mass dried out and the observations fell sharply, unlike the gradual decrease forecasted.
Fig. 11.28: 00 UTC 10 April 2005 RWFS run showing a dewpoint temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Fig. 11.29: 18 UTC 10 April 2005 RWFS run showing a dewpoint temperature (°C) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.
Wind Speed

The models had a low wind speed bias at the start of the 00 UTC run (Fig. 11.30). The saw-tooth pattern is again present in the final forecast indicating influence from the MAV-MOS. The observations drop sharply at the start of the event, which was not predicted by the models. A few hours into the event, the wind speed really picked up and remained high throughout the period, but the RWFS was late with the increase. For the 18 UTC run, most of the models and the RWFS final wind speed forecast were too low (Fig. 11.31).

Fig. 11.30: 00 UTC 10 April 2005 RWFS run showing a wind speed (m/s) time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.
Cloud Cover

The cloud cover forecasts from the mesoscale models at the beginning of the 00 UTC run called for scattered rather than broken cloud cover, and all the models were a few hours late with the increase to overcast (Fig. 11.32). A few models correctly forecast nearly 100% cloud cover for a time during this run. Halfway into the event, towards the end of the first model run period, the models dropped back off towards broken skies, and this caused the RWFS forecast to decrease the amounts as well.

For the 18 UTC run (Fig. 11.33), many of the models continued to forecast broken cloud cover; however, the Eta increased to overcast and that pulled the RWFS final forecast toward overcast. A few hours before the snow came to an end, the WRF and RUC started to decrease the cloud cover along with the MM5 and GFS an hour or two later. This caused the RWFS to underestimate the cloud cover at the end of the event. The MAV-MOS pulled it up a bit every third hour out to the end of the period as noted by the-saw saw tooth pattern.
Fig. 11.32: 00 UTC 10 April 2005 RWFS run showing a cloud cover time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.

Fig. 11.33: 18 UTC 10 April 2005 RWFS run showing a cloud cover time-series plot comparing the Denver METAR observations to the RWFS forecasts for the DIA site. Times when snow was falling are marked by the vertical lines.
Quantitative Precipitation Forecasts (QPF)

The start time for this event was approximately 5-6 UTC on 10 April 2005, and it lasted for about 24 hours (Fig. 11.34). The NCEP models had very light precipitation starting around 03 UTC. The oldest MM5 had precipitation starting around 05 UTC, while the 3 hour old MM5 had a start time around 06 UTC. The WRF models all had a start time between 06-08 UTC, while the RUC was the latest at 09 UTC. Many of the models picked up on the initial light precipitation. The RWFS did very well on the start time of this event during this run, but had the rates slightly high. The actual precipitation type at the start of the event was rain until 10 UTC when it turned to snow. Because of the warm air temperature forecast from 10-13 UTC (seen in Fig. 11.26), the RWFS final forecast held on to a precipitation type of rain for too long. The rain to snow changeover occurred after 13 UTC. For the 00 UTC run, the total liquid equivalent precipitation amounts forecast were quite close through 16 UTC, after which the RWFS rate became higher than the actual rate. The actual total liquid precipitation amount at the end of this period was 0.9 inches, while the RWFS predicted 1.3 inches. There was also absolutely no difference between the RWFS forecast with or without the precipitation thresholds for this run.

For the 18 UTC run, the RWFS forecast continued the trend of having a higher than actual precipitation rate (Fig. 11.35). The forecast precipitation type also changed from snow to rain around 23 UTC and then back to snow at 05 UTC. In reality, it was actually all snow. The timing of the end of the event was forecast fairly well. The actual total liquid accumulation amount during this period was 0.7 inches, while the RWFS predicted 0.9 inches. The main difference between the RWFS forecasts, with and without the precipitation thresholds applied, was that the “no threshold” forecast had an even higher precipitation rate and a later end time, which was further from the truth in this case.

This was a major snow event for Denver, and because of the warm bias in the predicted air temperature, the total snow depth amounts were less than actual even though the RWFS predicted more liquid equivalent precipitation than was measured.
Fig. 11.34: 00 UTC 10 April 2005 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.

Fig. 11.35: 18 UTC 10 April 2005 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.
Results and Recommendations: The case studies illustrate several issues that need additional investigation. The biggest surprise was the large discrepancies between the weather models in predicting air and dew point temperature, wind speed, cloud cover, and precipitation. None of the models consistently outperformed the others for any parameter.

Some models had more skill at forecasting air temperature while others were more skilled at dew point. All the models were too dry (low dewpoint temperatures) and most had difficulty predicting 100% cloudy conditions. The models also had a low wind speed bias overall. Some of these deficiencies can be traced to the fact that the Denver area experiences shallow, moist frontal systems that are not well captured by the models. The fronts often arrive hours before they are predicted bringing along moist, cool air and thin, shallow cloud layers.

These findings support the conclusion that an intelligent data fusion system should be used to optimize an ensemble of forecasts. The RWFS was able to demonstrate more skill overall than any of the individual forecast members as illustrated in Section 10.2.1. There are still open questions on how to best configure the RWFS to make it more responsive to rapidly changing conditions and how to select the appropriate type and number of forecast members.

The findings also support the concept of presenting weather prediction results in probabilistic terms because there are clearly times when the atmosphere is more predictable than others. Users should be made aware of the certainty of specific predictions. More research is required to determine the best approaches to use to present uncertainty to end users.

12 ROAD CONDITION AND TREATMENT MODULE (RCTM) RESULTS

12.1 RCTM Overview

Reapplying the prototype RCTM, which was configured and tailored for Iowa DOT, to Colorado DOT and the E-470 Authority proved challenging. Iowa DOT used anti-icing techniques to optimize both safety and efficiency. Treatments were applied only when conditions were about to transition into a hazardous regime (ice on the roads or snow building up on the pavement). Colorado’s E-470 Authority operation is different in that it is heavily focused on maintaining a clear or wet roadway at all times and prefers to keep the trucks on the road throughout the storm event. The E-470 Authority’s tendency is to apply treatments at all times during a storm.

Several changes were made to the system (post-season) to account for this “continuous” treatment strategy. Colorado DOT (CDOT) utilizes a strategy similar to Iowa DOT; however, the treatment strategy shown here is optimized for E-470, since they were the target maintenance operation. Details are given at the end of this analysis of changes that
were made after this analysis was performed to improve the portability of the RCTM not only between different maintenance operations but also to differentiate strategies between routes in the same maintenance region.

The analysis presented here is more limited in scope than last year’s treatment performance analysis. Case studies are shown that detail what recommendations the end-season version of the RCTM would have made. Modifications were made at the end of the season to adjust performance based on observed failure modes. Some changes were made to correct errors, thereby improving system performance, and other changes were simply made to increase the flexibility and usability of the RCTM. The following changes were made to the RCTM in preparation for MDSS Release 4.0:4

- Modified the handling of cleared roads with snow continuing to fall for input into SNTHERM. The system now leaves a small amount of snow on the surface which reduces temperature variations during an active storm. This more closely mimics actual conditions after plowing and treatment, when a thin layer of snow/slush will form during snowfall.
- Added the ability to control the treatment strategy. Users can now configure the route to recommend treatments “ONTRIGGER” or “CONTINUOUS”. The on trigger strategy recommends treatments when the system finds a chemical or plow-only treatment trigger (icy or snow covered roads). Continuous treatments look for new treatments as soon as the last treatment is finished.
- Added ability to handle multiple forms of chemicals (dry, pre-wet, or liquid).
- Added several new chemicals: Calcium Magnesium Acetate, Potassium Acetate, Caliber, and Ice Slicer.
- Integrated blowing snow potential algorithm into determination of chemical rate. Rates are increased with increasing blowing snow potential values.
- Revised the code to handle snow on the road at the initial (SNTHERM) time-step by executing a treatment in the first hour (chemical or plow-only as appropriate).
- Added additional sensitivity parameters to make the fine-tuning of recommendations simpler.
- Delayed treatment execution when rain is occurring prior to treatment triggering event (user adjustable).
- Further simplification of code logic, including the elimination of two software files that were used to convert RWFS to RCTM data structures (calc_chem.cc and calc_treatment.cc).
- Added code to better track the phase of the water on the roadway (dry, wet, chemically-wet, chemical-ice, snow and ice).
- Added site-by-site (route-by-route) chemical/treatment configuration, including independent control of pre-treatment chemical type and form.
- Added a treatment explanation string to summarize why a treatment was or wasn’t recommended.
- Added ability to handle multiple chemical types (for example, NaCl followed by MgCl₂). Residual chemicals from the first treatment are assumed to be the new

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4 MDSS Release-4.0 code and documentation will be made publicly available during the fall of 2005.
chemical. This includes output of the chemical rates in the appropriate units (gals/lane-mile or lbs/lane-mile).

12.2 RCTM Case Study Overview

The RCTM is responsible for generating treatment recommendations based on current and forecasted weather and road conditions. The recommendations are constrained by the types of treatments allowed on the roadway (chemical types, forms and ranges) and by the required level-of-service on the road (bare pavement, snow-covered, etc). The RCTM engine is also utilized to predict conditions based on either hypothetical “what-if” treatment scenarios and/or user-entered actual treatments. The RCTM considers the entire storm life-cycle for characterizing the overall storm conditions and for recommending treatment strategies. Referring to Fig. 12.1, the storm life-cycle includes not only the in-storm conditions when precipitation is falling, but also the pre- and post-storm road conditions. Pre-storm conditions control the application or pre-treatment chemicals (such as liquid brine) that are used to prevent icing at precipitation onset. Post-storm conditions (including road temperature and residual water on the pavement) are utilized to protect against re-freezing of the roads after the precipitation has stopped.

![Full Storm Life Cycle](image)

*Fig. 12.1 Illustration of the complete storm life-cycle.*
In analyzing cases, these three zones of treatment (pre-storm, in-storm and post-precipitation) must be examined to see if the correct treatment strategy has been employed.

A total of twelve case studies are examined in this report. Each case study has three regions to focus on: E-470 routes, Denver area CDOT routes, and CDOT mountain pass routes. In some cases the weather may be clear in one region and poor in another; therefore, not all of the cases focus on all of the regions. Only E-470 actively used the MDSS during this winter, the CDOT users were using the MDSS for informational purposes only, primarily for the weather and road condition predictions. Figure 12.2 shows the various regions and routes as shown on the MDSS display.

As mentioned previously, the verification analysis was limited in scope. We primarily focused on the failure modes of the prototype system and on treatment recommendations.
that were clearly improper (based on user feedback and expert analysis). A summary is provided for each case. A snapshot of the weather and treatment recommendations is then shown along with an analysis of the system’s performance.

Since neither CDOT nor E-470 have the ability to record treatment applications in real time during this period, only cursory (subjective) verification of the RCTM recommendations were possible. Only forecasted weather conditions were utilized; no attempt was made to go back and analyze how treatment recommendations might have changed based on the weather conditions that actually occurred.

All times are in local Mountain Time, unless otherwise noted, and all results in this section are based on the RCTM as revised at the end of the winter 2004-2005 field demonstration corresponding to MDSS Release-4.0.

The “Event Summary” page from the MDSS display is used to illustrate the overall storm situation and treatment recommendations. The event summary page (for an example see Fig. 12.3) shows the time series of several key weather and road variables. Starting from the top, the type of precipitation declared by the MDSS is shown in graphical form (rain, ice, or snow). The next chart uses a bar chart to show the relative probability of each type of precipitation (while the declared precipitation may have been rain, there may be a reasonable chance of snow instead). The forecasted, untreated, snow accumulation on the roadway are shown in the third chart. Even with no treatment, the chart will sometimes show decreases in snow depth based on melting and compaction. Road temperatures are shown next, with the solid horizontal line indicating freezing.

Colder temperatures require more chemical. For some chemicals, very cold temperatures make treatments ineffective and result in plow-only recommendations. The last of the forecasted condition variables shown in the Event Summary pages is wind speed and the accompanying blowing snow potential (none, low [yellow], medium [red], and high [magenta]). Blowing snow will increase treatment recommendations to compensate for additional snow on the road surface.

At the bottom of the Event Summary page, the MDSS displays the recommended treatment action. Each truck icon tells the user that a treatment is needed at that marked hour. There are three basic treatments: pre-treat, apply chemicals, and plow. The pre-treat and chemical applications will also specify the rate and type of chemical to be used. In the examples shown, only NaCl is used for in-storm treatments and liquid salt brine (always 40 gallons/lane-mile) for pre-treatments.

12.2.1 RCTM Analysis November 10th, 2004

As shown in Figures 12.3 – 12.6, the E-470 region on November 10th primarily faced a rain event on warm roads that ended with some light snow and below freezing pavement temperatures. The southern end of the region (MSSA) had more snow than the northern end, but all routes required some level of treatment because of the below freezing pavement temperatures and existing water on the roadway. The treatment strategies
recommended for these routes correctly suppressed pre-treatment applications due to a combination of warm pre-storm roads and rain prior to the freezing event. The MSSA recommendation was for three treatments of NaCl at 60 lbs/lane-mile (Fig. 12.3). The second treatment is applied at roughly midnight some three hours after precipitation has stopped. This treatment is still valid because water has not completely evaporated from the road surface and the chemical solution drops below effective levels. The last treatment is applied just prior to the onset of an additional light snow period. MSSC (Fig. 12.4) is similar to MSSA, except that the secondary snow is not present, and therefore, there are only two treatment applications recommended.

At MSSD (Fig. 12.5), the main event remains all rain and road temperatures remain elevated throughout the first wave of precipitation. However, the road slowly cools overnight and the remaining water on the road surface requires two 60 lbs/lane-mile treatments. The evaporation calculation within RCTM is a crude estimation, and in this case, it would appear that only the first of the two treatment applications was likely necessary to protect the road overnight. Finally, MSSE (Fig. 12.6) is similar to MSSD, except that only one treatment application of 60 lbs/lane-mile is recommended. However, the secondary snow between 9 PM and Midnight on the 11th is not treated at all. In looking at the underlying data, it appears that the forecasted precipitation was so light that the system did not recommend treatment. E-470 has an aggressive treatment strategy, and if this light snow did fall, they likely would have treated, while many other agencies may not have.

Fig. 12.3 Event summary page for MSSA on November 10th-11th, 2004
Fig. 12.4 Event summary page for MSSC on November 10th-11th, 2004

Fig. 12.5 Event summary page for MSSD on November 10th-11th, 2004
The Denver CDOT routes are south and west of the E-470 region on higher terrain (rising from approximately 5,300 ft to 6,500 ft) and typically experience weather that is slightly colder and snowier than E-470. In this case (Figs. 12.7-12.12), the far western route of I-70 at Floyd Hill (Fig. 12.7) experienced significantly more snow than the other routes (although the total snow only reached 1.5 inches). The storm has already started in this example, although the snow is extremely light at the beginning of the storm. Three 100 lbs/lane-mile treatments are recommended starting at the first hour followed by an 80 lbs/lane-mile and a 60 lbs/lane-mile treatment all spaced to allow for the round trip time of the Floyd Hill route (essentially continuous treatments). The last two treatments occur after the main event and are a little more spread out. The first 60 lbs/lane-mile treatment at 5 AM on the 11th is designed to prevent the standing water from refreezing. Similarly, the last treatment also protects the road after another brief predicted period of snow. Since the system started when snow was already falling, no pre-treatment recommendations were made. The treatments at the beginning are heavier in anticipation of the heavier snow that follows. Subsequent treatments are lower despite continued snow because of residual chemicals from previous treatments.
Rain is predicted for the rest of the routes (12.8-12.12), similar to the E-470 routes. However, the rain eventually turns to snow – typically slightly heavier rates than the E-470 region. As for E-470, the initial rain and warm roads suppress any pre-treatment recommendations. The heavy initial rain rates, however, typically make the initial treatment recommendation the heaviest, and the heavier snow amounts result in more overall treatments. The system offsets chemical treatments when rain occurs prior to ice forming on the road. However, the offset is fixed (configurable by the user, but the same for all storms) -- no adjustment is currently made based on the intensity of the preceding rainfall. The differences in initial treatments indicate that a more dynamic shift based on the rainfall intensity (reducing the offset for heavy rainfall) may be more optimal for conserving chemicals.
Fig. 12.8 Event summary page for Genesee on November 10th-11th, 2004

Fig. 12.9 Event summary page for Morrison on November 10th-11th, 2004
Fig. 12.10 Event summary page for I25 @ Exit 191 on November 10th-11th, 2004

Fig. 12.11 Event summary page for Surrey Ridge on November 10th-11th, 2004
Finally, the mountain pass region experienced only light levels of snow. However, these mountain pass routes were often not reset by the users to clear old snow from previous storms off the pavement. As such, they serve as good test cases for issues related to snow on the road at the beginning of the time-series. In real life, this snow can be left on the roadway for several reasons: the snow could be building up so fast that the previous treatments were insufficient to keep the road clear; the operator may be unable to maintain the roads due to equipment breakdown or availability; and/or the operator may choose to leave the road with snow because the required level-of-service allows it.

Looking at Figures 12.13 (Dowd) and 12.14 (Vail), the initial snow depth is just over 1” which also happens to be the plow trigger depth. As such, the system recommends a plow operation be performed to clear the road, this is then followed by two treatments to safeguard the road from re-freezing since pavement temperatures are near freezing. Adjustments were made after this analysis to allow the system to recommend chemical treatments in cases where the road is initially cold enough to cause standing water to freeze. The Wolcott route (Fig. 12.15) never sees significant snow and no residual snow is present at start-up. Therefore, no treatment action is recommended on these routes. This figure does, however, illustrate an issue with the road temperature model. Notice that the temperature curves show a significant increase on the morning of the 11th. This happens despite the fact that cloud cover is generally present and there is even a brief period of snow. In a crude attempt to correct for this over-heating of the road surface, a thin layer of snow is added to the SNTHERM input at the hour that snow occurs (11AM on the 11th). The addition of this layer causes a sharp spike downward in the road temperature. This correction is less noticeable for extended snow events, and it is likely
that several factors cause the temperature curve to spike upward during a time of what should be heavier cloud cover: (1) the solar radiation levels in the thin atmosphere of Denver caused large spikes in the road temperatures even when cloud cover is present; (2) cloud cover in the mountainous regions of Denver is harder to quantify than in the plains of Iowa; and (3) SNTHERM has a difficult time handling very thin layers of snow. The hard correction to 32 deg F during snow events was utilized to keep SNTHERM from melting away the snow too quickly. In any event, more work needs to be done on handling adjustments to the pavement temperature when either snow falls or snow is removed mechanically or chemically.

Fig. 12.13 Event summary page for Dowd Junction on November 10th-11th, 2004
Fig. 12.14 Event summary page for Vail Pass on November 10th-11th, 2004

Fig. 12.15 Event summary page for Wolcott on November 10th-11th, 2004
12.2.2 RCTM Analysis November 27th, 2004

The storm on November 27th blanketed the E-470 and Denver CDOT region with 2-4” of snow. The impact of the snow was similar on all the routes throughout this region and so were the treatment recommendations. As such, the example plots are limited to some representative examples. Figures 12.16 and 12.17 show the event summary page for E-470’s MSSA and CDOT’s Floyd Hill routes. In both cases, a pre-treatment application of 40 gals/lane-mile of liquid brine (the icon shown in the illustration is incorrectly labeled IceBan) is recommended. This pre-treatment is placed six hours prior to the start of precipitation despite the warm pre-storm roads. However, the roads in Colorado quickly change temperatures and the recommendation of a pre-treatment was confirmed by both CDOT and E-470 users in post-demonstration briefings. After the pre-treatment, a series of NaCl treatments are recommended. A brief interruption in the snow on the MSSA route results in no recommended treatments from about 2AM to 7AM on the 27th. Thereafter, treatments are steady at the minimum 60 lbs/lane-mile treatment level. At the Floyd Hill interchange, treatments are steady as the snow is continuous; however, treatments are reduced at the end of the storm when only very light snow is falling.

Fig. 12.16 Event summary page for MSSA on November 27th-28th, 2004
The mountain pass routes were also very similar; therefore, only the Dowd Junction route is shown (Fig. 12.18). Here, the snow is much heavier (over 8") and there is residual snow on the roadway as the system starts up. An immediate recommendation is made to plow the existing snow off the road. As mentioned earlier, logic in the final version 4.0 release would result in a chemical application being recommended in addition to the plowing. During the storm, heavy NaCl treatments are recommended (200 lbs/lane-mile) and these treatments eventually taper to 100 and then 60 lbs/lane-mile as the storm winds down.
12.2.3  RCTM Analysis January 29\textsuperscript{th}–30\textsuperscript{th}, 2005

The January 29\textsuperscript{th} storm was a weak storm with very light snow and marginal pavement temperatures. However, this case did yield a good example of the RCTM’s ability to protect the road before, during and after an event. As shown in Fig. 12.19, the recommendation for this storm was to pre-treat with 40 gals/lane-mile of brine to protect the road from freezing just as the storm started (again the icon shown in the illustration is incorrectly labeled IceBan). This was followed by an in-storm treatment of 60 lbs/lane-mile of NaCl to keep roads ice-free during the snow event. Finally, a recommendation is made for an additional 60 lbs/lane-mile to protect the road from re-freezing after the snow has stopped but before the road has dried out.
12.2.4 RCTM Analysis February 12th-13th, 2005

Only the mountain pass routes were impacted by snow on February 12th. Temperatures were well below freezing on all routes resulting in excellent treatment recommendations. The Vail Pass route was experiencing heavy blowing snow late in the storm, and as shown in Fig. 12.20, the treatment recommendations were increased from 60-80 to 160 lbs/lane-mile to compensate for the elevated blowing snow potential alert.
12.2.5 RCTM Analysis April 9th-10th, 2005

By far, the strongest snow event occurred on April 9th and 10th, 2005. While road temperatures and ambient temperatures before the event were very warm (~70°F air temperatures and 100°F road temperatures), heavy snow combined with heavy blowing snow to inundate most of the Denver area. Forecasted snow accumulations ranged from 2” to over 10” (western Denver) and blowing snow potential levels on many of the E-470 routes were high throughout much of the storm. When the RCTM ran in real-time, many of the routes yielded no treatments and it was discovered after the storm that the warm roads were suppressing chemical treatments. Subsequent changes to the rules of practice logic and the aforementioned modification to SNATHERM for road temperatures during snow events yielded superior results. In the post-season briefing, both CDOT and E-470 indicated that the new recommendations were closer (though still often under-recommending) to those performed in the field. The under-reporting, however, was primarily due to the RCTM limitation of one truck per route. Winter maintenance crews were added by E-470 allowing them to plow or double treat certain sections of roadway. The treatment explanation string added in MDSS Release-4.0 warns users that the recommended treatment will not keep the road clear and that tandem treatments may be needed.

Figures 12.21-12.23 show the event summary page for some of the E-470 routes. All of the forecasts for E-470 indicated that the storm would start as rain. In these situations, the RCTM is designed to suppress pre-treatment recommendations. In addition, the start time
of the first regular treatment is delayed to reduce direct dilution from rainfall. The southern MSSA route (Fig. 12.21) shows heavy snow and blowing snow for an extended period of time. A total of ten treatments are recommended, many of them at or just above the minimum 60 lbs/lane-mile level. E-470 applied many more treatments during the storm than the recommendation, and at much higher levels. Much of this difference can be explained by the difference in snow and pavement temperature forecasts. The system still has difficulty when road temperatures are predicted to be at or just above freezing. Sensitivity parameters have been added in MDSS Release-4.0 to allow users more flexibility in tuning the recommendations for their particular region and operations.

Fig. 12.21 Event summary for MSSA April 9th, 2005

The story is similar for MSSC (Fig. 12.22) and MSSD (Fig. 12.23), where pavement temperatures, despite a constant snowfall, stay near freezing early and slowly creep back above freezing late in the storm. These above freezing temperatures both reduce the recommended application rate early and suppress treatments late in the storm. The MSSD treatments tend to be heavier though less frequent than MSSA and MSSC despite lower overall snow totals. The heavier treatment is explained by the relatively heavier amounts of rain that fall prior to the snow and the heavier water content of the snow that does fall.
Fig. 12.22 Event summary for MSSC April 9th, 2005

Fig. 12.23 Event summary for MSSD April 9th, 2005
The Denver CDOT routes experience primarily snow during this event, and the forecast calls for heavy amounts of snow at Floyd Hill and Genesee. Figures 12.24 – 12.26 illustrate selected CDOT routes; the forecasted impact of the storm and the resultant recommended treatment action. These heavy amounts of snow result in heavy treatments throughout the storm. Road temperatures on these routes tend to stay under freezing making the chemical calculation more reliable and consistent throughout the storm.

Finally, Fig. 12.27 shows the I-70@Wolcott route for this same storm. Note that the recommended treatments have a gap from about 3 p.m. to 10 p.m. on the 10th. The treatment recommendations cease because the road temperatures, despite capping the road with a thin layer of snow, still indicate a dramatic rise in that period. Capturing the correct pavement temperature forecast both during a storm and as a result of executed treatments is critical to dependable treatment recommendations.
Fig. 12.25 Event summary for Genesee on April 9th, 2005

Fig. 12.26 Event summary for Surrey Ridge on April 9th, 2005
12.3 Overall treatment verification summary and conclusions

In total, twelve cases were examined in detail over this past winter. Table 12.1 lists the cases studied and individual route comments where warranted. Only a small sample of those case studies was presented here as much of the analysis was the same for other cases. The rules of practice module continues to be an evolving technology. Different climates, treatment strategies and road characteristics require that the system be flexible in addressing the needs of the user. As listed in the overview section, many changes have been made to allow users to tune the system to their region and routes. Blowing snow adjustments that were cited last year as lacking in the system have been added to increase treatment rate recommendations as blowing snow levels increase. The RCTM still struggles in cases with road temperatures slightly above freezing; although treatment recommendations are no longer suppressed, the chemical rates are often still a bit too low. The sensitivity adjustment capability added this spring should make it easier to fine tune the algorithm in these situations.
Overall, the new RTCM code (Release-4.0 version) performed well utilizing the latest improvements. Both CDOT and E-470 users indicated in post-demonstration briefings that the new system recommendations were much more reasonable.

Table 12.1 Listing of cases studied for testing and refining RCTM.

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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

Key: ✓ Treatment recommendation was reasonable for predicted weather conditions
      ✗ No snow or triggering events
      1 Treatment amount low due to warm roads (user adjustments added in Release-4.0)
      2 Road temperature peak was too high for conditions causing suppressed treatments
      3 Late secondary snow not pretreated (bug fixed in Release-4.0)
      4 Residual snow at start up was not cleared or only plowed when chemicals should have been used (fixed in Release-4.0)
      5 Secondary snowfall was not treated or treated too late (fixed in Release-4.0)

13 VERIFICATION OF ENSEMBLE MESOSCALE FORECAST MODELS

For the 2005 MDSS demonstration in Colorado the FSL model ensemble consisted of two different mesoscale, or regional, models (MM5 and WRF) with lateral boundaries from the Eta model provided by the NWS National Center for Environmental Prediction. The mesoscale models were initialized each hour with updated satellite, radar, and RWIS data each hour. MM5 was run out to 24 hr, and WRF to 18 hr, because of processing limitations. The ensemble modeling domain is illustrated in Fig 13.1.
Fig. 13.1: Modeling domain for MM5 and WRF during the 2005 MDSS Demonstration.

This is an example of how the model outputs were presented in real time on FSL’s web page (http://laps.fsl.noaa.gov/mdss).

Each ensemble member was initialized using the LAPS hot-start method of diabatic initialization. The Eta model, which provided lateral boundary conditions, is updated only four times daily 0300, 0900, 1500, and 2100 UTC (8 PM, 2 AM, 8 AM and 2 PM MST), so lateral boundary data were interpolated in time for the off-cycle MDSS model runs.

The object of verifying these or any forecasts is to determine if predictors are capable of adding quality to the forecast service. The concept behind ensemble modeling is that a properly combined group of forecasts can provide a better forecast than any single predictor in the ensemble.

Shelter-level (2m) Temperature and Dewpoint and Tower-level (10m) Winds

The MDSS model forecasts between 1 October 2004 and 31 April 2005 are evaluated by comparisons against hourly METAR observations of surface temperature, wind, and dewpoint (humidity). Bulk 12-hr forecast verification statistics (RMSE and bias) are given in the following tables. The corresponding table from the 2004 demonstration which was conducted in Iowa is provided for comparison. The Iowa domain is quite flat; the Colorado domain has very complex topography, which is one of the reasons the 2005 demonstration was conducted there.
<table>
<thead>
<tr>
<th></th>
<th>Temperature (deg C)</th>
<th>Wind speed (m/s)</th>
<th>Dewpoint (deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE    bias</td>
<td>RMSE Bias</td>
<td>RMSE bias</td>
</tr>
<tr>
<td>MM5</td>
<td>3.2   +0.2</td>
<td>2.4 +1.6</td>
<td>3.7 +1.5</td>
</tr>
<tr>
<td>WRF</td>
<td>3.0   +1.3</td>
<td>2.3 +1.3</td>
<td>3.7 +2.2</td>
</tr>
<tr>
<td>Eta</td>
<td>2.7   +0.5</td>
<td>2.7 -0.2</td>
<td>2.6 +1.7</td>
</tr>
</tbody>
</table>

Table 13.1. 12-hr forecast verification statistics from the 2004 MDSS demonstration conducted in Iowa.

<table>
<thead>
<tr>
<th></th>
<th>Temperature (deg C)</th>
<th>Wind speed (m/s)</th>
<th>Dewpoint (deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE    bias</td>
<td>RMSE Bias</td>
<td>RMSE bias</td>
</tr>
<tr>
<td>MM5</td>
<td>3.2   +0.9</td>
<td>2.2 +0.7</td>
<td>3.3 +1.5</td>
</tr>
<tr>
<td>WRF</td>
<td>3.2   +1.0</td>
<td>2.2 +1.2</td>
<td>3.9 +2.2</td>
</tr>
<tr>
<td>Eta</td>
<td>2.3   +0.5</td>
<td>2.1 +0.4</td>
<td>2.8 +1.1</td>
</tr>
</tbody>
</table>

Table 13.2. 12-hr forecast verification statistics from the 2005 MDSS demonstration conducted in Colorado.

Here are the main results:

- All three models had warm-biased temperatures and dewpoints, which is the same result determined in last year’s MDSS demonstration. The reasons are still unknown. The dewpoint forecasts were not quite as accurate as they were in Iowa, probably because the spatial variability of humidity is much greater in complex terrain. The other statistics are not much different from one domain to the next.

- The Eta model makes better 12-hr temperature and dewpoint forecasts than either mesoscale model. We surmised last year that the advantage for the Eta model is because it has surface flux formulations that are closely tied and tuned to its Land Surface Modules (LSM), which characterize the earth surface by vegetation type, roughness, albedo, moisture content, land use, etc. This remains an area of critical need in NWP research for road weather.

- The wind speed verification suggests that the models are a bit more accurate for winds in complex terrain (Table 13.2) than in flatter terrain (Table 13.1). This is
probably because RMSE wind speed errors are correlated with mean wind speed (i.e., a
10% error on a 10 m/s wind speed leads to 1 m/s RMSE, whereas a 10% error on a 25
m/s wind speed leads to 2.5 m/s RMSE). Wind speeds in complex terrain are generally
slightly lower than winds measured in the flatlands, simply because the effective surface
friction is greater.

These statistics are calculated over all model runs. Stratifying the statistics by time of
day reveals additional interesting information about their respective performance
characteristics.

Fig. 13.2: Temperature forecast verification for 2005 00 UTC MDSS model runs.
Fig. 13.3: Temperature verification statistics for 2005 12 UTC MDSS model runs.

Figures 13.2 and 13.3 show temperature verification statistics from all the 00 UTC and 12 UTC MDSS model runs.

- The RMSE statistics for the mesoscale models are remarkably consistent at 3.0 to 3.5 degrees Celsius, regardless of time of day.

- The Eta model is consistently a full Celsius degree more accurate at all times.

- The warm bias noted in the bulk statistics above for all models is also evident here.

- There is no apparent diurnal trend toward the error statistics for any model, in sharp contrast to indications from the 2004 experiment conducted in the flatlands of the US. This is may be because radiatively cooled air, which is poorly predicted by the mesoscale models, is generated uniformly over flat terrain, but drains into compact ribbons (valleys) in complex terrain. Drainage flows are associated with fog, road frost, and other phenomena critical to roadway operations – this remains a critical research need.

A closer look at more of the model runs, not just 00 UTC and 12 UTC, reveals some interesting but troubling behavior.
**Figure 13.4:** Time series of temperature forecast biases from MM5.

**Fig. 13.3:** Time series of temperature forecast biases from WRF.
In Figures 13.4 and 13.5 the time series of forecast temperature bias for each model run between 00 UTC and 12 UTC inclusive are plotted and aligned according to valid time. Very strange behavior is seen in the 05 – 09 UTC model runs from MM5, and the 05 – 07 UTC model runs from WRF. The other model runs shown here exhibit very consistent bias amounts, but these few model runs show much colder biases than the others for the first few hours of model integration.

It seems likely that anomalous model performance indications such as these are the result of a small number of “spectacular” forecast busts. Possible examples of such failures were noted in two April snowstorms when the models were too warm (see Fig. 13.4). Unfortunately, the model errors propagated through the MDSS processing sequence, leading to very poor guidance.
Fig. 13.4: Model temperature forecasts and corresponding verification observations for the April 10-11 2005 snowstorm.
In Figure 13.6 note that extremely warm temperature biases were produced by all three models for the case of 10-11 April 2005. All three models “caught up” with reality at around 12Z, which is approximately sunrise locally. Similar error patterns showed up in the case of 28-29 April (not shown). Note that this response is not tied to any particular forecast lead time, indicating that other types of forcing error, which would perhaps “wash away” with increasing integration time, were not the problem. Instead, the models must have been initialized with inadequate data concerning the development or advection of very shallow and cold air at the surface. Such air layers can be as little as a hundred meters thick, which is thinner than the lowest model layer, with overlying air as much as 15°C warmer. This class of NWP error is familiar to High Plains meteorologists; the solution is greater vertical resolution in the lowest model layers, which will approximately triple the amount of computing time required to make model forecasts. Keeping NWP computing platforms affordable will probably require automated detection of this type of meteorology and supplemental nested model runs of some sort. This is an area of critical research need.

Precipitation Verification

Model precipitation forecasts are compared to hourly precipitation gauge data from the HADS dataset, which is quality-controlled and distributed the day after observation. The hourly reports are aggregated into 3-hr amounts for this report. The reported statistics are ESS, which is the equitable skill score, and areal bias. ESS ranges from 1.0 for perfect performance to 0.0 for forecasts of no skill at all, essentially equivalent to a random variable being used as a predictor. Areal bias, not to be confused with biases in magnitude which are used above for the state variables, is 1.0 if the model covers the correct fraction of the domain with precipitation at or above a particular precipitation threshold; values above 1.0 indicate overforecasting.

Figures 13.7 and 13.8 present 3-hr precipitation verification from the 2004 Demonstration in Iowa and the 2005 Demonstration in Colorado, respectively.
Fig. 13.5: Three-hour precipitation forecast verification from the 2004 MDSS demonstration in Iowa.

Fig. 13.6: Three-hour precipitation forecast verification from the 2005 MDSS demonstration in Colorado.
Here are the main results:

- The mesoscale models, MM5 and WRF, did not perform much better than the Eta model at 3-hr precipitation forecasting during the 2005 Demonstration in Colorado (Fig. 13.8); in fact, the Eta actually did better than the MM5 model for some precipitation thresholds. This is in sharp contrast to the results from the prior demonstration in Iowa (Fig. 13.7), where the mesoscale models made better precipitation forecasts than the Eta across the board. This is probably because in Colorado’s mountainous terrain, saturated updrafts are often fixed to locations where winds are blowing uphill, so that short-range precipitation forecasts are not nearly as sensitive to initial conditions as they are in Iowa. In the flatlands, most precipitation is generated by dynamic meteorology such as jet streaks and frontal overrunning. The LAPS hot-start method of diabatic initialization does a good job of placing saturated updrafts where they belong. The Eta’s data assimilation system does not do as well.

- The performance of MM5, relative to the other models, was not as good in 2005 as it was in 2004 (and in other parallel modeling system experiments conducted at FSL). This traces back to an error in the implementation of diabatic initialization in conjunction with a new microphysics algorithm used in MM5.

Fig. 13.7: Six-hour precipitation forecast verification from the 2005 demonstration.
The 6-hr precipitation verification (Fig. 13.9) suggests that all three models have similar ESS statistics. This is consistent with earlier findings that the benefits of the LAPS hot-start initialization become less noticeable after about 6 hours for forecast integration. The underforecast bias exhibited by the Eta model at the higher precipitation thresholds is a consistent signal in virtually every precipitation verification exercise, and a behavior well known to operational forecasters.

14 ANALYSIS OF OBSERVED ROAD SURFACE TEMPERATURES

The heat balance at the Earth’s surface is complicated by heat and moisture flows occurring in many modes. Heat can be transferred to and from the surface from above by all three principal methods of heat transfer: conduction, convection, and radiation. Radiation components include both short wave and long wave. Evaporation and condensation are additional modes of heat transfer at the surface. Phase change heat transfer is also a factor with freezing and melting of moisture occurring frequently in cold regions. Heat and mass transfer with the soil underlying the surface also impacts the surface energy balance. If the surface itself is assumed to have no finite mass, then its temperature will be determined by the balance of these energy transfers at that point. Accurately modeling all of these complex heat flow components to achieve a precise surface temperature prediction is a challenging task.

Equally challenging is the task of making an accurate measurement of surface temperature, particularly on the surface of a high traffic roadway. Essentially any effort to measure a surface temperature will in some manner disturb the surface temperature distribution by introduction of a material with differing thermal and/or optical properties. A temperature sensor placed right at the surface may not mimic the surface itself with respect to thermal, optical, and textural properties, each an important factor in heat transfer with the surroundings.

A third complicating factor in comparing measured and modeled results for surface temperature is the input data used to drive the surface temperature model. Most often complete measured weather data are not available at the site where the comparison is to be done and local dissimilarities due to terrain, as well as variation in weather over even moderate distances, can generate significant errors. Our task here is compounded by the fact that for the operational use of our surface temperature model we need to rely on forecasted weather data with its inherent inaccuracies. In the post analysis, we can at least eliminate this impact by using measured weather data, understanding fully that it is still encumbered with the other limitations discussed above.

Hence, when making comparisons between modeled and measured surface temperatures, it is imperative that we keep in mind the limitations of each result. While we are keenly aware of the limitations of the CRREL developed SNTHERM surface temperature model, and our ability to generate precise weather to drive the model, we did not have a good grasp of what the expected measurement errors might be. To get a sense of these measurement errors, surface temperature measurements were made at several of the locations where the roadway temperatures were being measured during the 2003-2004
MDSS Field Demonstration in Iowa, the results of which are reported in the 2003-2004 Technical Performance Assessment Report (NCAR, 2004). For the 2004-2005 MDSS Field Demonstration in Colorado discussed here, similar measurements were also performed. In both cases, the same two devices were used: an infrared camera (FLIR ThermaCAM® S60) and a portable infrared surface thermometer (Exergen D-501).

For the 2003-2004 MDSS Iowa Demonstration, measurements were taken under both day and night clear sky conditions when it was felt the thermal and optical properties of the roadway temperature measurement “pucks” were more likely to cause the highest degree of measurements errors. For the 2004-2005 MDSS Colorado Demonstration, the daytime clear sky condition was possible during the observation period, while the nighttime condition observed a very thin cloud layer. Data reduction from the IR images for the 2004-2005 MDSS Demonstration followed a similar procedure using our infrared image analysis software; although an adjustment was made to achieve more appropriate background temperature estimates. In addition, an “effective emissivity” was also used to account for the impact of the objects in the background whose temperatures and view factors with respect to the points of measurement were not directly assessed. This effective emissivity was computed independently at each site by finding the emissivity value where the pavement temperature measured by the IR image analysis agreed most closely with that found by the infrared surface thermometer (IRT). After these adjustments were made the temperatures from the IR image analysis were determined by selecting areas within the center of the “puck”, as well as areas of similar size in the pavement area adjacent to the puck, and calculating their apparent mean temperature.

When sampling with the infrared camera, the unit was handheld at approximately 1 meter off the pavement surface directly over the RWIS pavement temperature sensor. Normally three images would be taken at each location in immediate succession. Either directly preceding or following the sampling with the infrared camera, the IRT would be used to sample. This instrument is placed in contact with the pavement as the design of the sensor housing allows for emissivity compensated temperature measurements when used in this manner. IRT readings were normally taken at three locations on the roadway adjacent to the RWIS sensor and three locations on the RWIS sensor itself, avoiding locations close to its edge or the chemical sampling depression. The entire sampling process for both the infrared camera and IRT measurements would be accomplished in about 2-3 minutes, and hence, all readings could be reasonably assumed to be from the same point in time. Except as noted below, the data being generated by the RWIS sensor itself at that period in time were also collected later. These interval data were interpolated to obtain approximate RWIS data at the time of the infrared camera and IRT readings.

Measurements were made at three sites on the E-470 roadway where RWIS stations are located: Smokey Hill exit, Platte River Bridge (approach and deck), and 6th Ave Parkway exit (where E-470 Headquarters is located). The 6th Ave Parkway exit was not visited during the day for logistical reasons, and in addition, it should be noted that the RWIS site there was not functional during either time period. All daytime measurements were made on 16 November 2004 and all nighttime measurements were made on 17 November 2004. The results of our measurement are summarized in Table 14.1 below.
First looking at the measured surface temperatures of the puck and the adjoining pavement, by examining the results given in Table 14.1 it is seen that under daytime clear sky conditions, measurements made by infrared thermometer (IRT) and infrared camera (IR) show the puck to be warmer than the surrounding pavement. This is entirely consistent with our results from the 2003-2004 MDSS Demonstration field tests in Iowa (NCAR, 2004). On average, for the tests conducted during the 2004-2005 MDSS Demonstration field season for the daytime measurements, the puck was warmer than the surrounding pavement by 2.3°C as measured by the IRT and 1.7°C as measured by the IR camera.

Table 14.1: Measurement results for the infrared thermometer and the infrared camera compared to the temperatures reported by the RWIS.

<table>
<thead>
<tr>
<th>Location</th>
<th>Approx. Time</th>
<th>Avg. IRT Puck (°C)</th>
<th>Avg. IRT Pvt. (°C)</th>
<th>IRT diff. Pvt.-Puck (°C)</th>
<th>Observed RWIS puck (°C)</th>
<th>Avg. IR Camera Puck (°C)</th>
<th>Avg. IR Camera Pvt. (°C)</th>
<th>IR Camera Pvt.-Puck (°C)</th>
<th>IRT PVT puck -RWIS (°C)</th>
<th>IR Puck -RWIS (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smokey Hill</td>
<td>3:32</td>
<td>6.8</td>
<td>6.5</td>
<td>-0.3</td>
<td>6.0</td>
<td>0.5</td>
<td>-0.1</td>
<td>2.0</td>
<td>5.0</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>13:08</td>
<td>27.1</td>
<td>25.0</td>
<td>-2.1</td>
<td>27.4</td>
<td>25.1</td>
<td>-2.3</td>
<td>25.1</td>
<td>9.1</td>
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<tr>
<td></td>
<td>4:31</td>
<td>6.5</td>
<td>6.5</td>
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<td>1.5</td>
<td>-1.0</td>
<td>2.2</td>
<td>0.8</td>
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<tr>
<td></td>
<td>14:30</td>
<td>25.4</td>
<td>22.4</td>
<td>-3.0</td>
<td>24.1</td>
<td>22.4</td>
<td>-1.8</td>
<td>23.2</td>
<td>0.8</td>
<td>2.2</td>
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<tr>
<td></td>
<td>4:28</td>
<td>5.5</td>
<td>5.7</td>
<td>0.2</td>
<td>4.6</td>
<td>1.1</td>
<td>1.5</td>
<td>1.0</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>E-470 Headquarters</td>
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<td>6.5</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td></td>
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<tr>
<td>Night Avg.</td>
<td>6.4</td>
<td>6.2</td>
<td>0.2</td>
<td>5.2</td>
<td>1.0</td>
<td>1.1</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Day Avg.</td>
<td>23.8</td>
<td>21.5</td>
<td>-2.3</td>
<td>22.3</td>
<td>0.7</td>
<td>1.5</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

During the 2003-2004 MDSS Demonstration in Iowa under clear night skies, we saw the opposite effect as what has been observed during the day here, that is the puck temperature was lower than the surrounding pavement. During the night measurements conducted for the 2004-2005 MDSS Demonstration in Colorado, we had a very thin overcast sky, and we observed very little difference between puck and pavement temperatures under those conditions by IRT and IR methods, as can be noted from the results in Table 14.1 above.

Looking at the temperatures that the pucks were reporting at the RWIS stations, note that for the three sites where daytime clear sky measurements were made, the temperature that the pucks were reporting was indeed always higher than the surrounding pavement temperature as measured by IRT, on the average of 0.7°C. Interestingly, the same comparison with the measurements made during the night reveal that the RWIS reported temperatures consistently lower by a similar amount of 1.0°C on average. The results of both the day time and nighttime measurements comparing RWIS reported temperatures to IRT measured pavement temperatures are summarized in Figure 14.1.

A final comparison is made between the RWIS reported temperatures and the IRT measurements of the puck surface temperatures. From Table 14.1 note that the RWIS reported temperatures appear to have a “cold bias” for both the daytime and nighttime when compared to the puck temperature as determined by the IRT; on average the bias is
1.1°C at night and 1.5°C during the day, averaging 1.3°C across all measurements. The results of the RWIS reported versus IRT measured puck temperatures are summarized in Figure 14.2.

![RWIS Vs IRT on Pavement](image)

*Figure 14.1: RWIS reported temperatures compared to IRT measured pavement temperatures.*
The conditions under which the measurements were made during both the 2003-2004 and 2004-2005 MDSS Demonstrations were those under which the largest disagreement between the surface temperature forecast model, SNTHERM, and the observed surface temperatures was observed. Both the clear sky night and day conditions are conditions of high radiative heat transfer flux. Under precipitation conditions, high heat fluxes (caused by convective heat transfer in the case of rain and melting heat transfer in the case of snow) can also result. The surface temperature implications, however, are quite different. In the case of the precipitation induced heat fluxes, the heat sink/source of the precipitation will be much nearer to the surface temperature than the radiative sources and the resistances to heat transfer very small. Thus while the radiative fluxes will tend to accentuate differences in the materials, the convective and melting fluxes will tend to “wash” them out.

In light of this, one interpretation of these data could be that the roadway temperature sensors have a lower specific heat and/or higher thermal conductivity resulting in the sensors having a higher thermal diffusivity than the adjacent roadways; thus, they respond quickly to the radiative fluxes. Another possible interpretation would be that the thermal coupling between the roadway temperature sensor and the roadway underneath it is inadequate for the sensor in the roadway to emulate a solid, unbroken material. Of course, a possible combination of these effects would be another reasonable interpretation.
Results and Recommendations: Accurate road surface temperature prediction is arguably the most important advance that an operational MDSS could achieve. The measurements of pavement surface temperatures made during the 2003-2004 and 2004-2005 MDSS Demonstration season suggest that significant improvement in road surface temperature measurements may be needed to provide better benchmark and initial condition data for the road surface temperature forecast models. While the measurements here do not constitute a rigorous examination of the topic or represent a large enough sample to draw definitive conclusions from, they do suggest that there are significant errors being made by the RWIS stations examined in reporting actual pavement surface temperatures. The RWIS road temperature sensors can not be taken as an absolute standard against which models can be compared, or for that matter, calibrated against.

15 DISPLAY SOFTWARE

There were very few new features added to the display for the MDSS 2004-2005 winter demonstration.

The display was localized for forecast points, routes, and alert zones in Colorado (see Fig. 15.1). A few additional minor changes to the display included changing the background color scheme in order to easily distinguish it from previous versions, as well as implementing a shaded relief map for the background of the regional images.
Fig. 15.1. MDSS summary display, indicating colored dots and values for temperature.

The most significant addition to the display was the new road frost algorithm output, which was incorporated into the display as an additional alert type. The frost potential is identified by the same color scale used for weather, road condition, and blowing snow alerts. The frost alerts are shown as colored boxes in the alert panel and route view time bar.

Performance was similar to last year, even though over 25 users were authorized to view and select treatments simultaneously. Several users ran the display from laptop computers at their office and home and there were no common complaints about the display system.
16 ADDITIONAL RESEARCH NEEDS

The movement of the prototype MDSS from Iowa to Colorado highlighted several issues that were discussed throughout this report. The high elevation and complex terrain challenged the weather prediction models as they had difficulty predicting small-scale terrain-induced precipitation events, extreme diurnal air temperature fluctuations, shallow cold air masses, and the amount of insolation penetrating thin clouds.

The large variation in snow and ice control operations between E-470 and CDOT also complicated the demonstration as the prototype MDSS was not as configurable as it needed to be prior to the demonstration. Strong diurnal fluctuations in the road temperatures also helped to identify limitations in the rules of practice module, which were subsequently addressed through major revisions of the RCTM, which are encapsulated in MDSS Release-4.0.

Each MDSS field demonstration has been successful in identifying limitations in all components of the system from weather forecasting to treatment recommendations. Subsequent research and development efforts have resulted in system improvements that, through technology transfer and outreach activities, should facilitate the transition to operations by commercial weather service providers and others.

Although significant progress continues to be made in road weather forecasting and the development of the MDSS technologies, additional research is required to improve the performance of the components that contribute to the system. Additional research needs are summarized below:

**Numerical Weather Prediction**

1) Land Surface Modeling: Additional research is required to couple weather prediction models with land surface models. This is a relatively new area of research and one that is critical for predicting the surface and near surface conditions.

2) Boundary Layer Meteorology: Research is required to better understand the atmospheric processes (e.g., surface fluxes, etc.) and their interactions with the land surface. Predicting phenomena such as drainage flows, fog formation, shallow fronts, road frost, blowing dust and smoke are all highly dependent on understanding the science of the near surface boundary layer.

3) Weather Model Configuration: Research is required to explore factors that could improve near surface weather prediction. Model configuration variables including the number and distribution of model levels and selection of physics packages to optimize skill during winter events needs to be explored.

4) Data Assimilation: Additional research is required on the development of data assimilation techniques that can take advantage of current and emerging surface weather observations (e.g., vehicle based observations, short range radars, etc.) that have the potential for improving short range forecasts (0-12 hours).
5) **Clouds and Insolation**: Additional research is required to improve the prediction of clouds and insolation, as these parameters are critical for pavement temperature prediction.

**Pavement Condition Detection and Prediction**

1) **Effect of Insolation**: Additional research is required to understand how pavement temperature sensors (various models and brands) perform under varying insolation (direct and indirect radiation) conditions. Current results suggest that under conditions of strong solar loading, the accuracy of the pavement temperature sensors is reduced.

2) **Road Condition Sensing**: The accuracy of pavement chemical concentration and freezing temperate measurements is low and because of this poor performance, these data are not widely used by DOT personnel and not incorporated into systems such as the MDSS. Knowledge of the pavement chemical concentration and its incorporation into the MDSS would reduce the workload of DOT staff as they would not have to manually enter actual pavement condition information.

3) **Pavement Temperature Modeling**: Additional research is required to understand the interactions of differing chemical types with various forms of precipitation and the impact it has on pavement temperature. New pavement types such as porous asphalt also need to be studied so their temperature profile behavior can be properly modeled. The impact of traffic on pavement temperature and how traffic distributes chemicals needs to be studied.

4) **Utilization of Actual Treatment Data from Vehicles**: One of the largest deficiencies of the prototype MDSS is its inability to incorporate actual treatment data in near real-time. Currently, DOT personnel must enter actual treatment data once operations have begun. In most cases, time does not permit the manual entry process to occur, and future MDSS treatment recommendations are not initialized properly and hence inaccurate. Research is required to investigate optimal methods of incorporating GPS/AVL data from vehicles in near real time during winter events.

5) **Road/Bridge Frost**: Additional research is required to better understand the factors that influence the formation and dissipation of road and bridge frost. Improvements in bridge deck temperature prediction are needed and a better understanding of the gradients in air and dew point temperature near the pavement surface are needed. In addition, the characteristics of long wave radiation, which is important for pavement temperature prediction, for bridges crossing varying surfaces (e.g., rivers, highways, valleys, railbeds, etc.) needs to be understood to improve the prediction of bridge deck temperatures.

**General**

1) **Communication of Uncertainty**: The DOT users acknowledge that weather and road condition prediction is complex, particularly on road scales. They often requested that the information include terms of uncertainty (e.g., probability and/or confidence). The prototype MDSS included a graphical precipitation type product that indicated the
conditional probability of precipitation type and the pooled fund MDSS includes confidence intervals for some parameters. Additional work is required to research and develop methods for calculating uncertainty and understanding the human factors issues involved in presenting this information to end users.

17 REFERENCES


APPENDIX A

MDSS Colorado Field Demonstration
Winter 2004-2005

POINTS OF CONTACT LIST

The persons listed on this page are the primary technical leads on the MDSS software system and field verification data collection.

### MDSS Development Team

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Lead</td>
<td>Jim Cowie, NCAR</td>
<td>303-497-2831</td>
<td><a href="mailto:cowie@ucar.edu">cowie@ucar.edu</a></td>
</tr>
<tr>
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</tr>
<tr>
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<td><a href="mailto:myers@ucar.edu">myers@ucar.edu</a></td>
</tr>
<tr>
<td>Rules of Practice</td>
<td>Robert Hallowell, Lincoln Laboratory</td>
<td>781-981-3645 Cell: 603-566-8457</td>
<td><a href="mailto:bobh@ll.mit.edu">bobh@ll.mit.edu</a></td>
</tr>
<tr>
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<tr>
<td>Weather Models</td>
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<td><a href="mailto:Paul.J.Schultz@noaa.gov">Paul.J.Schultz@noaa.gov</a></td>
</tr>
<tr>
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<td>703-610-1754 Cell: 703-403-4987</td>
<td><a href="mailto:astern@mitretek.org">astern@mitretek.org</a></td>
</tr>
<tr>
<td>Road Weather Management Program</td>
<td>Paul Pisano, FHWA</td>
<td>202-366-1301</td>
<td><a href="mailto:Paul.pisano@fhwa.dot.gov">Paul.pisano@fhwa.dot.gov</a></td>
</tr>
</tbody>
</table>

### E-470 Public Highway Authority

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Director of Roadway and Land Management</td>
<td>Matt Alexander</td>
<td>303-537-3726</td>
<td><a href="mailto:malexander@e-470.com">malexander@e-470.com</a></td>
</tr>
<tr>
<td>Manager of Maintenance</td>
<td>Terry Gowen</td>
<td>303-537-3710</td>
<td><a href="mailto:tgowin@e-470.com">tgowin@e-470.com</a></td>
</tr>
<tr>
<td>Administrator</td>
<td>Micheli Watson</td>
<td>303-537-3747</td>
<td><a href="mailto:mwatson@e-470.com">mwatson@e-470.com</a></td>
</tr>
<tr>
<td>Maintenance Contractor</td>
<td>Dave Pickrell</td>
<td>720-490-7214</td>
<td><a href="mailto:tpickrell@aol.com">tpickrell@aol.com</a></td>
</tr>
</tbody>
</table>

### Colorado DOT

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWIS Administrator</td>
<td>Wayne Lupton</td>
<td>303-273-1840 303-263-3952 (cell)</td>
<td><a href="mailto:Wayne.Lupton@DOT.STATE.CO.US">Wayne.Lupton@DOT.STATE.CO.US</a></td>
</tr>
<tr>
<td>Garage – Federal to Morrison</td>
<td>Roy Smith</td>
<td>303-480-9870</td>
<td><a href="mailto:Roy.Smith@DOT.STATE.CO.US">Roy.Smith@DOT.STATE.CO.US</a></td>
</tr>
<tr>
<td>Garage – Morrison to Hidden Valley</td>
<td>Dave Schuessler</td>
<td>303-278-1777</td>
<td><a href="mailto:Dave.Schuessler@DOT.STATE.CO.US">Dave.Schuessler@DOT.STATE.CO.US</a></td>
</tr>
<tr>
<td>Garage – 1-25 and C470 to</td>
<td>Alfonso Martinez</td>
<td></td>
<td><a href="mailto:Alfonso.Martinez@dot.state.co.us">Alfonso.Martinez@dot.state.co.us</a></td>
</tr>
</tbody>
</table>
## Northwest Parkway

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrator</td>
<td>Lina Kheng</td>
<td>303-533-1209</td>
<td><a href="mailto:LKheng@nwpky.org">LKheng@nwpky.org</a></td>
</tr>
</tbody>
</table>
## APPENDIX B

### MDSS Field Demonstration Event Summary

**15 October 2004 – 15 April 2005**

<table>
<thead>
<tr>
<th>Demo Day</th>
<th>Date</th>
<th>Weather</th>
<th>System Notes</th>
<th>System Upgrades, Fixes and Refinements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fri, 15 Oct ‘04</td>
<td>DEN: --RA/DZ late afternoon/evening</td>
<td>Demonstration began</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DEN: Light showers forecast</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Sat, 16 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sun, 17 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mon, 18 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td>Updated the site layer traffic config files to use route treatment times per E-470.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Tue, 19 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Wed, 20 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Thr, 21 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Fri, 22 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Sat, 23 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Sun, 24 Oct ‘04</td>
<td>DEN: -DZ in the late afternoon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Mon, 25 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Tue, 26 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Wed, 27 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td>Installed new int_obs which includes climo-enhanced QC range checks for obs. Changed default QC ranges to tighten up allowable ranges for temp and precip vars. Installed new road_cond which reflects E-470 min and max solid chemical app rates.</td>
</tr>
<tr>
<td>14</td>
<td>Thr, 28 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Fri, 29 Oct ‘04</td>
<td>DEN: High wind event</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Sat, 30 Oct ‘04</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Sun, 31</td>
<td>DEN: RA-SN starting</td>
<td>System had FZ turning to</td>
<td>Two Power Hits: 8:30p and</td>
</tr>
</tbody>
</table>

172
<table>
<thead>
<tr>
<th>Date</th>
<th>Time/Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct ‘04</td>
<td>around 6p SN around 8p SN for the S E470 routes and RA-SN for the N routes with 2-12” predicted. Tr drops to 19 tomorrow night – seems a bit cold with warm ground yet. 9:30p – went down for good.</td>
</tr>
<tr>
<td>18 Mon, 1 Nov ‘04</td>
<td><strong>DEN:</strong> SN ending System held on to SN too long. Re-Installed new road_cond which reflects E-470 min and max solid chemical app rates. Re-set RCTM due to sntherm hanging. Added temporal interpolation of missing T, Td and Wsd for MADIS data that do not report regularly.</td>
</tr>
<tr>
<td>19 Tue, 2 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx Meso-models have very light rain/snow along the foothills tomorrow morn – nothing in MDSS. Installed new mtr_proc which changes how some precip is defined in the METARs and int_obs (i.e. snow pellets are now frozen instead of freezing precip). Bug fix in road_cond.</td>
</tr>
<tr>
<td>20 Wed, 3 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>21 Thr, 4 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>22 Fri, 5 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx Changed Tr to 33.5F from 35F for treatment trigger</td>
</tr>
<tr>
<td>23 Sat, 6 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>24 Sun, 7 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>25 Mon, 8 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx MDSS 8am update with RA starting around 12am turning to SN on 10th at 10pm-12am on the 11th with snow for the rest of the period</td>
</tr>
<tr>
<td>26 Tue, 9 Nov ‘04</td>
<td><strong>DEN:</strong> Scattered RA showers 0.05-0.1” of rain Installed new snow:liquid ratio code based on CRREL alg.</td>
</tr>
<tr>
<td>27 Wed, 10 Nov ‘04</td>
<td><strong>DEN:</strong> Scattered RA turned to SN started ~20Z-02Z About 0.5” of snow</td>
</tr>
<tr>
<td>28 Thr, 11 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>29 Fri, 12 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>30 Sat, 13 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>31 Sun, 14 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>32 Mon, 15 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>33 Tue, 16 Nov ‘04</td>
<td><strong>DEN:</strong> No significant wx</td>
</tr>
<tr>
<td>Date</td>
<td>Location</td>
</tr>
<tr>
<td>------------</td>
<td>----------------</td>
</tr>
<tr>
<td>17 Nov '04</td>
<td>DEN</td>
</tr>
<tr>
<td>18 Nov '04</td>
<td>DEN</td>
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<tr>
<td>19 Nov '04</td>
<td>DEN</td>
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<tr>
<td>20 Nov '04</td>
<td>DEN</td>
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<tr>
<td>21 Nov '04</td>
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<tr>
<td>22 Nov '04</td>
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<tr>
<td>23 Nov '04</td>
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<tr>
<td>24 Nov '04</td>
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<tr>
<td>25 Nov '04</td>
<td>DEN</td>
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<tr>
<td>26 Nov '04</td>
<td>DEN</td>
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<tr>
<td>27 Nov '04</td>
<td>DEN</td>
</tr>
<tr>
<td>28 Nov '04</td>
<td>DEN</td>
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<td>30 Nov '04</td>
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</tr>
<tr>
<td>01 Dec '04</td>
<td>DEN</td>
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<tr>
<td>02 Dec '04</td>
<td>DEN</td>
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<td>05 Dec '04</td>
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<td>06 Dec '04</td>
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<td>07 Dec '04</td>
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<tr>
<td>08 Dec '04</td>
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<tr>
<td>09 Dec '04</td>
<td>DEN</td>
</tr>
<tr>
<td>10 Dec '04</td>
<td>DEN</td>
</tr>
<tr>
<td>Date</td>
<td>Weather Event</td>
</tr>
<tr>
<td>------------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Sat, 11 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sun, 12 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Mon, 13 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Tue, 14 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Wed, 15 Dec '04</td>
<td>DEN: Snow showers developed a 6 pm local time and lasted 2-3 hrs dropping between a trace and 1 inch.</td>
</tr>
<tr>
<td>Thr, 16 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Fri, 17 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sat, 18 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sun, 19 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Mon, 20 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Tue, 21 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Wed, 22 Dec '04</td>
<td>DEN: Snow reported at DEN at 330a. APA at 2a. Snow ended around 10a.</td>
</tr>
<tr>
<td>Thr, 23 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Fri, 24 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sat, 25 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sun, 26 Dec '04</td>
<td>DEN: No significant wx</td>
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<tr>
<td>Mon, 27 Dec '04</td>
<td>DEN: No significant wx</td>
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<td>Tue, 28 Dec '04</td>
<td>DEN: No significant wx</td>
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<tr>
<td>Thr, 30 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Fri, 31 Dec '04</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sat, 1 Jan '05</td>
<td>DEN: No significant wx</td>
</tr>
</tbody>
</table>

Convective snow showers not picked up by FSL models. Some snow was predicted around Front Range. Model timing was off by several hours.

Met with E-470 staff to debrief on performance of system to date.

Changed recommended treatment chemical back to NaCl at request of E-470.

Timing and amounts for this event were pretty well forecast by mdss the day before.

Fix to RCTM to address bug in the initialization of road chemical state. Evap. rate was incorrect due to wspd and rh initialization probs.
<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Location</th>
<th>Description</th>
<th>Changes/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>Sun, 2 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>Mon, 3 Jan ’05</td>
<td>DEN: No significant wx FOG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>Tue, 4 Jan ’05</td>
<td>DEN: SN started around 5a, off and on all day some freezing drizzle in places as well early on. SN picked up again by 4p (~3”)</td>
<td>System started similar to NWS with 5-7” but gradually decreased and turned it more scattered during the afternoon. Seemed to do a good job…</td>
<td>Changed temp_interp to use a cubic spline instead of linear interp for instantaneous temps. Effects after 21h forecast.</td>
</tr>
<tr>
<td>83</td>
<td>Wed, 5 Jan ’05</td>
<td>DEN:.. became scattered in the early morning, filled back in around 7a and then started clearing out around 2p. Temps were in the single digits and low teens for this storm. (additional 1-2”)</td>
<td>…with decreasing the snow. Amounts looked reasonable throughout after initially being too high.</td>
<td>Display updates including: time stamp on printable images default chem. Is NaCl rather than MgCl</td>
</tr>
<tr>
<td>84</td>
<td>Thr, 6 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td>Display went down at the 00 UTC(5p local) update because of incompatibility of 48 snow accum with display</td>
</tr>
<tr>
<td>85</td>
<td>Fri, 7 Jan ’05</td>
<td>DEN: No significant wx Bill observed frost along Platte River this morning-roads seemed to be treated</td>
<td></td>
<td>Updated display to provide a 48 total snow accum</td>
</tr>
<tr>
<td>86</td>
<td>Sat, 8 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>Sun, 9 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>Mon, 10 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>Tue, 11 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td>SN forecast for Wed morning (2-6a) in 8a update (~1”). Later updates removed and then put back in.</td>
</tr>
<tr>
<td>90</td>
<td>Wed, 12 Jan ’05</td>
<td>DEN: SN started around 3a in Longmont but FZRA at DEN12Z and then SN. BJC obs missing from 5Z-12Z.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>91</td>
<td>Thr, 13 Jan ’05</td>
<td>DEN: Very light SN falling around 9p in Longmont.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>Fri, 14 Jan ’05</td>
<td>DEN: Very light SN falling at 3a (Boulder/Longmont – nothing at DIA ob). Just a dusting.</td>
<td>No precip forecasted. WRF captured Mtnwave cloud pretty well at 8a. MM5 had no clouds.</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>Sat, 15 Jan ’05</td>
<td>DEN: -SN reported from 1-10Z at DEN. Little to no accum.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>Sun, 16 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Day(s)</td>
<td>Summary</td>
<td></td>
<td></td>
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<tr>
<td>------------</td>
<td>----------------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>95 Mon, 17 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>96 Tue, 18 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>97 Wed, 19 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>98 Thr, 20 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99 Fri, 21 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 Sat, 22 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>101 Sun, 23 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>102 Mon, 24 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>103 Tue, 25 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>104 Wed, 26 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>105 Thr, 27 Jan ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>106 Fri, 28 Jan ’05</td>
<td>DEN: No significant wx</td>
<td>System going for about 1-1.5” SN for Sat night.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>107 Sat, 29 Jan ’05</td>
<td>DEN: Light RA/SN mix reported at DEN from 10-11p. RA in Longmont 6p-10p with a trace of SN on the ground in the morn 8a. (light flurries at 9a as well)</td>
<td>System slowly increased amounts as the day went by</td>
<td></td>
<td></td>
</tr>
<tr>
<td>108 Sun, 30 Jan ’05</td>
<td>DEN: SN reported starting at 9p</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>109 Mon, 31 Jan ’05</td>
<td>DEN: SN ended around 6a: 6” Boulder, 1” Longmont, 3” Louisville</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110 Tue, 1 Feb ’05</td>
<td>DEN: Very light SN dusting across the area – no impact.</td>
<td>Bill observed frost on ground but not bridges. Changed DMOS config for all models and both systems (nt/st) so the three conditional prob are default eqtns. Added cpoX variables to the list of statically weighted variables in nt system so they share same weights as pop and qpf and have 0 biases.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>111 Wed, 2 Feb ’05</td>
<td>DEN: No significant wx</td>
<td>Fix bug in METAR obs processing that was causing false negatives for conditional precip types</td>
<td></td>
<td></td>
</tr>
<tr>
<td>112 Thr, 3 Feb ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>113 Fri, 4 Feb ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>114 Sat, 5 Feb ’05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>115 Sun, 6 Feb ’05</td>
<td>DEN: light SN reported</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Event Description</td>
<td></td>
<td></td>
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<tr>
<td>------------</td>
<td>------------------------------------------------------------------------------------</td>
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<td></td>
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</tr>
<tr>
<td>116 Mon, 7 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>116 Mon, 7 Feb ‘05</td>
<td>Cleaned up bad road temp obs to fix range on display</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>117 Tue, 8 Feb ‘05</td>
<td>DEN: light SN reported 7:30-9:30. Less than an inch in Longmont. FC ~3”.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>117 Tue, 8 Feb ‘05</td>
<td>Fixed a problem with the bias (set =0 for qpf, pop, cprob; weights still evolve, just not bias) in the short term system</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>117 Tue, 8 Feb ‘05</td>
<td>MDSS down because RAL web server down from 9p 2/7 – 9a 2/8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>118 Wed, 9 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>119 Thr, 10 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120 Fri, 11 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>121 Sat, 12 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>122 Sun, 13 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123 Mon, 14 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>124 Tue, 15 Feb ‘05</td>
<td>DEN: –SN started in Boulder 5a, ended by ~11a. ~2” Boulder, 6” FC</td>
<td></td>
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</tr>
<tr>
<td>124 Tue, 15 Feb ‘05</td>
<td>MM5 had SN 9a-12p with highest amounts around FC (3” max anywhere). WRF had SN 10a-3p with a hole over FC.</td>
<td></td>
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</tr>
<tr>
<td>125 Wed, 16 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>126 Thr, 17 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>127 Fri, 18 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>128 Sat, 19 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>129 Sun, 20 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130 Mon, 21 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>131 Tue, 22 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>132 Wed, 23 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>133 Thr, 24 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>134 Fri, 25 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>135 Sat, 26 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>136 Sun, 27 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>137 Mon, 28 Feb ‘05</td>
<td>DEN: No significant wx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>138 Tue, 1 DEN: No significant wx</td>
<td>SW and LW radiation weights</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

178
<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar ‘05</td>
<td>changed to 49% MM5, 49% WRF and 1% ETA</td>
</tr>
<tr>
<td>139 Wed, 2 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>140 Thr, 3 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>141 Fri, 4 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>142 Sat, 5 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>143 Sun, 6 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>144 Mon, 7 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>145 Tue, 8 Mar ‘05</td>
<td>DEN: Strong front came through between 9-11a with very high winds and some RA/SN/PE.</td>
</tr>
<tr>
<td>146 Wed, 9 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>147 Thr, 10 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>148 Fri, 11 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>149 Sat, 12 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>150 Sun, 13 Mar ‘05</td>
<td>DEN: 05Z–15Z –SN reported. Amounts varied w/ 3-5&quot; along E470, 5-7&quot; on the south end of DEN.</td>
</tr>
<tr>
<td>151 Mon, 14 Mar ‘05</td>
<td>DEN: Occl scattered SN flurries</td>
</tr>
<tr>
<td>152 Tue, 15 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>153 Wed, 16 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>154 Thr, 17 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>155 Fri, 18 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>156 Sat, 19 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>157 Sun, 20 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>158 Mon, 21 Mar ‘05</td>
<td>DEN: RA mixed with SN from 12Z-19Z at DEN (~0.3&quot; precip reported in E470 area). All RN in Boulder, SN/RA east – no accum.</td>
</tr>
<tr>
<td>159 Tue, 22 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>160 Wed, 23 Mar ‘05</td>
<td>DEN: RA 5-7p or so</td>
</tr>
<tr>
<td>161 Thr, 24 Mar ‘05</td>
<td>DEN: SN</td>
</tr>
<tr>
<td>Date</td>
<td>Day</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Fri, 25 Mar ‘05</td>
<td>DEN: FZDZ in the morn</td>
</tr>
<tr>
<td>Sat, 26 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sun, 27 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Mon, 28 Mar ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Tue, 29 Mar ‘05</td>
<td>DEN: RA in Boulder, but I think it dissipated before DIA (possibly a few sprinkles ~3p according to radar)</td>
</tr>
<tr>
<td>Wed, 30 Mar ‘05</td>
<td>DEN: reported SN at 0053 (T=4, wind northerly) and continued into Thr morn.</td>
</tr>
<tr>
<td>Thr, 31 Mar ‘05</td>
<td>DEN: SN diminishing in the morn.</td>
</tr>
<tr>
<td>Fri, 1 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sat, 2 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sun, 3 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Mon, 4 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Tue, 5 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Wed, 6 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Thr, 7 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Fri, 8 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sat, 9 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Sun, 10 Apr ‘05</td>
<td>RA began ~midnight turned to SN around 6am and came down all day…</td>
</tr>
<tr>
<td>Mon, 11 Apr ‘05</td>
<td>SN ended early Z time. DEN ~12”</td>
</tr>
<tr>
<td>Tue, 12 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Wed, 13 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Thr, 14 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
<tr>
<td>Fri, 15 Apr ‘05</td>
<td>DEN: No significant wx</td>
</tr>
</tbody>
</table>
APPENDIX C

GEONOR Precipitation Gauge located at Denver International Airport

Fig. C.1: GEONOR precipitation gauge with a DFIR shield.