Program for Climate, Ecosystem and Fire Applications

Verification of North Carolina Mixing Height Forecasts for Smoke Management

Final Report

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CEFA Report 10-02 March 2010

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March 2010

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EXECUTIVE SUMMARY

The North Carolina Division of Forest Resources (NCDFR) launched 18 radiosondes during February/March 2006 to measure vertical profiles of temperature, humidity and wind speed/direction in conjunction with prescribed fires. From an operational perspective, data from radiosondes provides fire management with decision-support meteorological information of the near surface and upper air. Key information available from these data is the observed mixing height, corresponding transport wind and other calculated indices, such as a ventilation index. The primary project goal was to use the radiosonde observations for quantitative verification of National Weather Service mixing height forecasts. Upper-air observations from NWS were also examined. The verification analysis serves the following purposes:

1. Provide a quantitative indication of the forecast skill and uncertainty of the mixing height.
2. Provide a quantitative indication of forecast skill for scientific researchers to utilize in determining how meteorological models and forecasts can be improved.
3. Raise national awareness of the importance of having verification information in conjunction with decisions that have inherent risk of impacting safety and valued resources.

The project deliverables include:

1. A dataset of archived forecasts and observations through March 2006.
2. A presentation of the project results at the March 2007 Fire and Fuels Conference.
3. This project report.

Local sounding data are useful near a prescribed burn because they 1) provide information directly relevant to the burn location; and 2) allow for local verification rather than relying on an observation taken a large distance from the burn. However, the NWS forecasts proved challenging to quantitatively verify because of their non-specific forecast times of “today” and “last night” and “tomorrow”. “Today” forecasts refer to the afternoon of the same day the forecast was made (during the morning), “last night” forecasts refer to the previous night forecast for today and “yesterday” refers to the next afternoon forecasts. Correlations using NCDFR observations were .66, .70 and .23 for “today”, “last night” and “tomorrow”, respectively. The two forecasts with the shortest lead-time (“today” and “last night”) have reasonably high correlations, but the previous day forecast has a much lower correlation. All three correlations are affected by the sounding time and a non-specific forecast time. Further, the small sample of 18 observations (and for five forecast times a mixing height forecast was not available) makes it difficult to draw comprehensive conclusions. Nonetheless, having a local sounding associated with a burn does provide for valuable localized atmospheric information that can aid in tactical decisions, and provides more specific data for forecast verification.

1. Introduction

The North Carolina Division of Forest Resources (NCDFR) planned to launch 95 radiosondes in early 2006 related to prescribed fire activities. Local sounding data are useful near a prescribed burn because they 1) provide information directly relevant to the burn location; and 2) allow for local verification rather than relying on an observation taken a large distance from the burn. Key information related to burning available from sounding data includes the observed mixing height, corresponding transport wind and other calculated indices such as the ventilation rate (mixing height times the mean layer wind speed).

This study focused on the mixing height – an important atmospheric element in smoke management. The mixing height is the height of an atmospheric layer that would allow for the rise and dispersion of smoke given sufficient buoyancy for lift. High mixing heights allow for a smoke parcel to rise, while an inversion keeps smoke trapped near the surface.

Ultimately due to operational burn activity and personnel availability, only 18 radiosondes were launched during the study period. The primary project goal was to use the local radiosonde observations for quantitative verification of National Weather Service (NWS) mixing height forecasts.

The verification analysis serves the following purposes:

- Provide a quantitative indication of the skill and uncertainty of the mixing height for NCDFR fire management.
- Provide a quantitative indication of forecast skill for scientific researchers to utilize in determining how meteorological models and forecasts can be improved.
- Raise national awareness of the importance of having verification information in conjunction with decisions that have inherent risk of impacting safety and valued resources.

The project deliverables include:

1. A dataset of archived forecasts and observations.
2. A presentation of the project results at the March 2007 Fire and Fuels Conference.
3. This project report.

The project was collaborative between NCDFR and the Desert Research Institute (DRI) program for Climate, Ecosystem and Fire Applications (CEFA). This report provides descriptions of the task elements and deliverables, and summarizes the project findings.

2. Project Area

The National Weather Service (NWS) issues North Carolina forecasts by zones (Figure 1). The area of interest for this project included the entire state of North Carolina, though the data were primarily collected in the western and eastern portions of the state (Figure 2). Mixing height forecasts for relevant zones where a local sounding was taken were compared to the radiosonde observations collected at the locations shown in Figure 2. Blue dots indicate locations of standard NWS sounding locations; the two sites analyzed in this study are MHX (Newport) and GSO (Piedmont Triad International Airport). Note that the spatial distribution of NWS sounding locations is relatively sparse around the region for analyzing local atmospheric conditions. Also, MHX is a coastal location, and is frequently under a marine inversion layer, thus limiting the use of this station for assessing mixing heights further inland. The red locations are those soundings recorded by NCDFR. Though 18 soundings were analyzed, only nine red dots are visible indicating location overlap for some soundings.

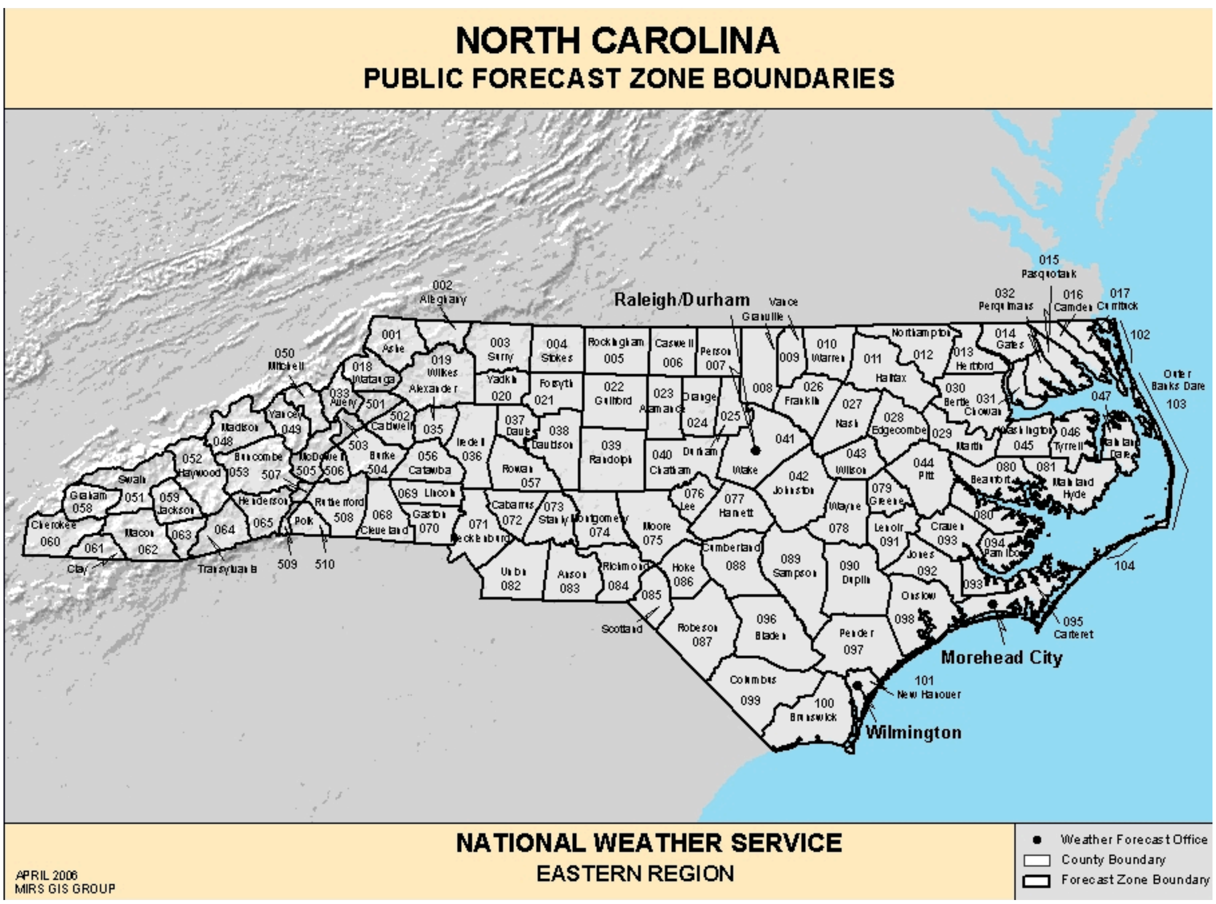

Figure 1. NWS forecast zones in North Carolina.

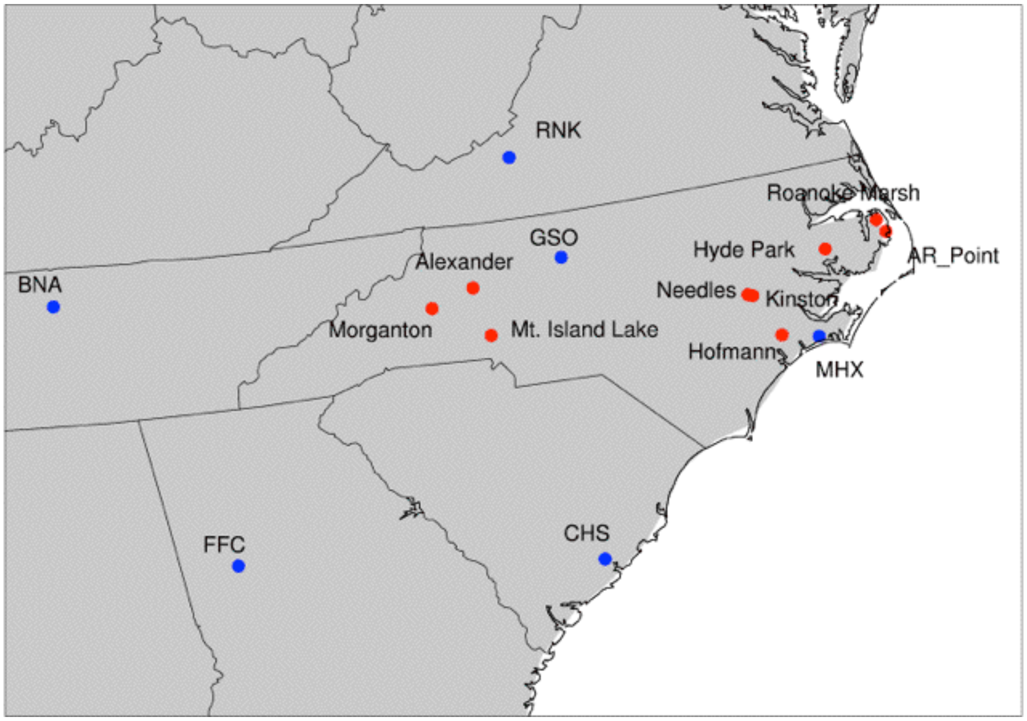

Figure 2. Sounding locations used in this study. Blue dots indicate NWS daily sounding sites, and red dots locations of NCDFR soundings.

3. Deliverables and Results

Task element 1: Data collection of forecasts and radiosonde observations.

NWS mixing height forecasts were retrieved and archived through the Western Regional Climate Center (WRCC). Figure 3 is an example NWS fire weather forecast containing mixing height (the mixing height forecast is denoted by the bold text). Sounding data for MHX and GSO were also retrieved from the WRCC archive. NCDFR provided the data from the 18 local soundings observed in February and March 2006.

Table 1 below includes a list of NCDFR radiosonde locations used in the study, and the NWS office that was responsible for each location's forecast. These offices are also the locations of the NWS twice-daily (00 and 12 UTC) soundings. The NWS forecast zone is also given.

```
FNUS52 KCAE 010912
FWFCAE
FWFCAE 010905
FIRE WEATHER FORECAST
NATIONAL WEATHER SERVICE COLUMBIA SC
405 AM EST THU JAN 1 2004
.DISCUSSION...
HIGH PRESSURE WILL CONTINUE BUILDING ACROSS THE AREA
THROUGH NEW
YEARS DAY. AS THE HIGH MOVES TO THE EAST OF THE AREA
FRIDAY THROUGH
SATURDAY, CLOUDS WILL GRADUALLY INCREASE.
SCZ015-016-020>022-020311-
CHESTERFIELD-FAIRFIELD-KERSHAW-LANCASTER-NEWBERRY-
INCLUDING THE CITIES OF...LANCASTER...NEWBERRY
257 AM EST THU JAN 1 2004
                      TODAY        TONIGHT      FRI
CLOUD AMOUNT          PCLDY        MCLDY        CLOUDY
PRECIP CHC (%)        0            0            20
PRECIP TYPE           NONE         NONE         SHOWERS
MAX/MIN TEMP          62           38           64
AM WIND               N  2                      S  4
PM WIND               E  3         SE  1        SW  6
PRECIP AMOUNT         0.00         0.00         0.02
PRECIP DURATION       0            0            1
HUMIDITY (%)          24           92           46
HAINES INDEX          4            4            4
LAL                   1            1            1
PRECIP BEGIN                                    11 AM
PRECIP END                                      6 PM
MIXING HGT            2000                      2500
TRANSPORT WIND        S  5                      SW 10
VENTILATION RATE      10000                     25000
DISPERSION                         7PM-8AM/PO
DSI                   1                         1
```

Figure 3. Example NWS fire weather forecast; mixing height is shown in bold.

Table 1. Sounding locations, responsible NWS office and NWS forecast zone.

Sounding Site	Latitude	Longitude	NWS Office	NWS Forecast Zone
Central Pungo / Hyde Park	35.66	-76.58	MHX	80
Kinston	35.33	-77.61	MHX	91
Needles	35.35	-77.67	MHX	91
Hofmann	34.87	-77.34	MHX	98
Alexander	35.91	-81.14	GSO	35
Mt. Island Lake	35.39	-81.00	GSO	69-71
Roanoke Marsh	35.85	-75.86	MHX	47
Needles	35.35	-77.67	MHX	91
AR_Point P	35.71	-75.77	MHX	47
Morganton	35.74	-81.70	GSO	54

*Task element 2**:** Statistical analysis of forecasted versus observed mixing height.*

2.1 Holzworth method

The Holzworth method (Holzworth 1964; 1967; 1972) is commonly used for mixing height determination utilizing the 00 and 12 UTC radiosonde measurements, and has an assumption of the surface temperature remaining dry adiabatic (e.g., constant potential temperature) through a well-mixed layer. The morning mixing height is defined as the level above ground at which the dry adiabatic ascent of the morning minimum surface temperature plus 5°C intersects the vertical temperature profile measured at 1200 UTC. The afternoon mixing height is based on the level above ground at which the adiabatic ascent of the maximum surface temperature intersects the 0000 UTC temperature profile. This latter method is often applied to obtain a daily forecast of the afternoon mixing height utilizing the daily forecast maximum surface temperature and 1200 UTC sounding. The Holzworth methodology above is applied to the 12 UTC NWS soundings of the burn day, and 00 UTC soundings the following day (which represents a late afternoon sounding of the burn day). For the NCDFR soundings, both variations of applying a +5°C adjustment and no adjustment (0°C) is done. The zero adjustment should be more representative of the actual height though, and the +5°C adjustment is done simply for comparison.

2.2 Comparison of NCDFR mixing height and NWS forecasts

Table 2 provides summary statistics for the NCDFR observed and NWS forecasted mixing heights for the three forecast periods - morning forecast for the same day afternoon (“Today”), the previous night forecast for today (“Last night”) and today’s forecast from yesterday afternoon (“Yesterday”), respectively. This table is based on a zero Holzworth adjustment. The statistical median (used instead of mean given the small sample size) row in the table shows that the “Today” forecast was typically 1200 feet higher than the observed values, while the “Last Night” forecast was typically 700 feet higher the observed values, and the “Yesterday” forecast was typically 1500 higher than observed. These median differences represent the typical forecast bias of over-forecasting; that is, the forecasts tend to be higher than observed. However, an important caveat to this result is that the sounding does not necessarily represent the maximum mixing height value, and thus, the seemingly over-forecasting may not be a significant issue.

The maximum observed value in Table 2 is within 600 feet of the highest forecast value, and the observed minimum is as much as 2700 feet lower than the lowest forecast value. The date of the forecast maximum/minimum value is not the same as the observed maximum/minimum value. These numbers are provided to get a sense of forecast and observed distribution. This is better represented in Figure 4, which shows boxplots of the observed and forecast mixing height distributions. The observed NCDFR box shows a larger range than the forecasts, and nearly all of the forecast values are above the median observed value. But again, this could be due in part to the timing of the sounding in relation to the maximum mixing height of the day.

Table 2. Summary statistics for NWS forecasts and NCDFR observed mixing heights (feet). Correlation is based on a Spearman rank calculation, and bias is forecast minus observed. The header row labels indicate when the forecast was made for "Today".

Statistic	Observed	Today	Last Night	Yesterday
Median	3408	4622	4152	4962
Maximum	7259	7543	6773	6593
Minimum	335	3001	2511	2601
Correlation		.66	.70	.23
Bias		1214	744	1554

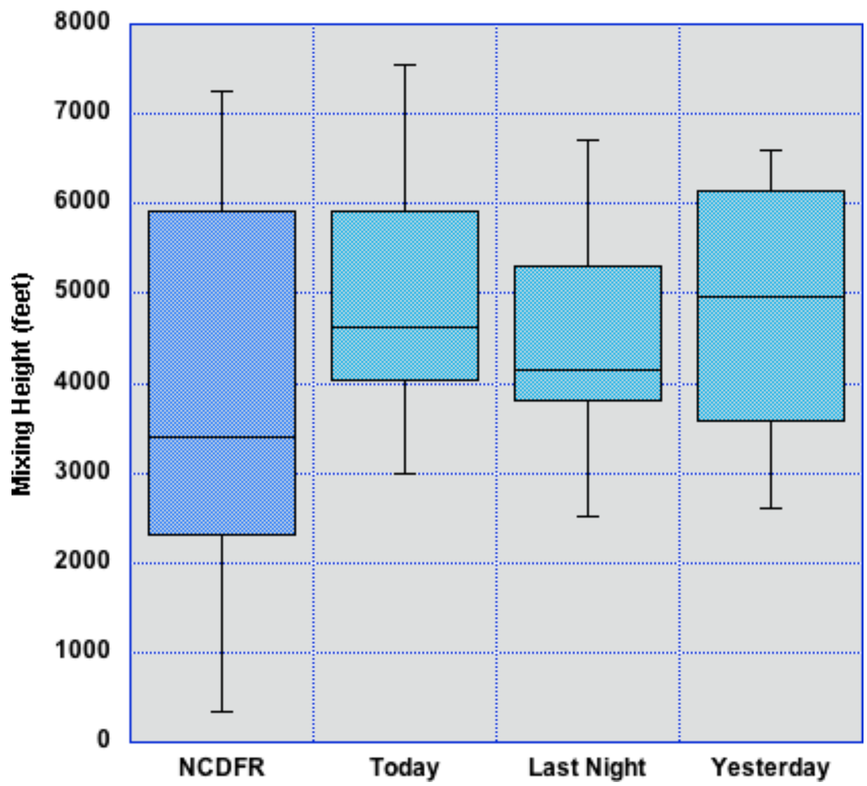

Figure 4. Boxplots of observed (NCDFR) and NWS forecast mixing heights. Box represents the range of 25% to 75% percentile values, and bars represent minimum and maximum values. The median value is indicated by the line through the box.

Also shown in Table 2 are the correlations between the observed and respective forecast based on the Spearman rank calculation (this was used instead of Pearson because it is a more robust method for smaller sample sizes and is resistant to outliers). The fairly high correlations for "Today" and "Last Night" are similar (.66 and .70, respectively), but the value for the "Yesterday" is quite low in comparison (.23). This lower value suggests that even given the caveat of the actual maximum mixing height time in relation to the observation time, there still seems to be an unexplained problem with the previous day's forecast.

Figure 5 shows scatterplots of NCDRF observed mixing height with the "Today", "Last Night" and "Yesterday" forecasts. Each blue dot indicates the observed value in relation to the forecast value. Dots on the line would indicate perfect forecasts. Dots above the diagonal line indicate that forecast mixing heights larger than observed, and vice versa. These plots graphically show the bias discussed in relation to Table 2.

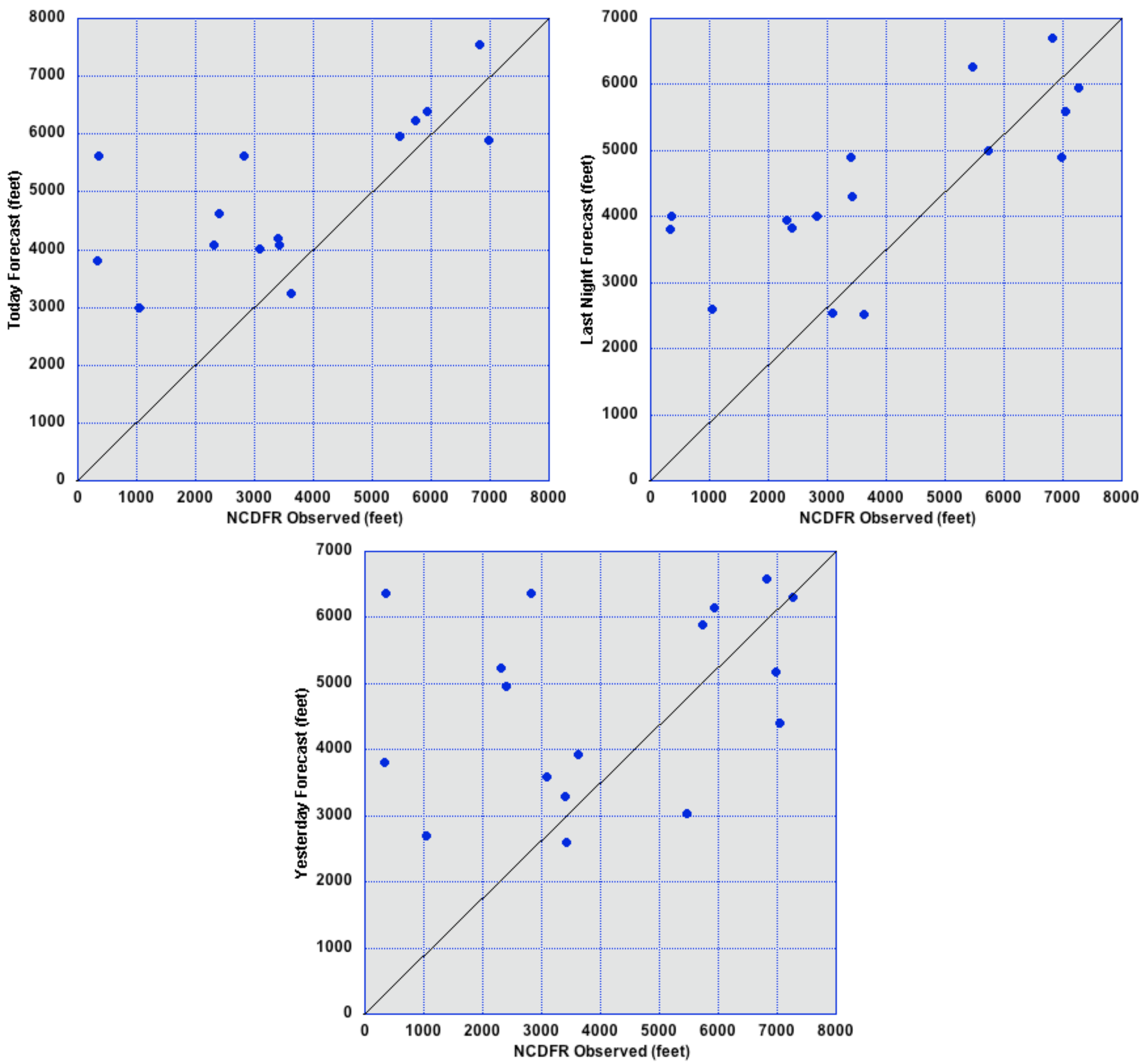

Figure 5. Scatterplots of NWS forecast versus NCDFR observed mixing heights.

2.3 Comparison of NWS observed mixing height and NWS forecasts

Table 3 summarizes the statistics for NWS forecasts in comparison to NWS soundings taken at MHX and GSO. For the comparison, the sounding closest to the fire was used. Unlike the NCDFR soundings, these are taken at the fixed time of 12 UTC. The median observed mixing height is approximately 800 feet lower than for the NCDFR soundings. While the minimum values between NWS and NCDFR are similar, the NWS maximum value is larger by nearly 1600 feet, but this is due to a single outlier case. The forecast bias using the NWS soundings is approximately 800 feet higher than for NCDFR (Table 2). The correlations for the NWS soundings are also much lower than for NCDFR locations. This suggests one of the benefits of having a local sounding.

Table 3. Summary statistics for NWS forecasts and NWS 12 UTC observed mixing heights (feet). Correlation is based on a Spearman rank calculation, and bias is forecast minus observed. The header row labels indicate when the forecast was made for "Today".

Statistic	Observed	Today	Last Night	Yesterday
Median	2580	4622	4152	4962
Maximum	8853	7543	6773	6593
Minimum	318	3001	2511	2601
Correlation		.44	.62	.14
Bias		2042	1572	2382

Figure 6 shows scatterplots of NWS observed versus the NWS forecast similar to Figure 5. In all cases, the points show a mostly positive bias in the forecasts; that is an over-forecast of the mixing height.

2.4 Comparison of NCDFR and NWS observed mixing height

Figure 7 shows boxplot distributions of NCDFR and NWS 12 UTC mixing heights. Note that except for the one large outlier and the minimum value, the NWS values are generally lower than NCDFR. This likely mostly due to the observation time of the soundings; NCDFR soundings occurred mostly in the early afternoon, and the NWS soundings occurred at 12 UTC, or morning local time. The further highlights the value of having a sounding during the afternoon near the typical peak of the mixing height time.

2.4 Comparison of NCDFR mixing height methods

Figure 8 shows boxplots of the NCDFR mixing heights using the Holzworth method with no adjustment and with a +5°C adjustment. Given that nearly all of the sounding launch times were in early to mid-afternoon, the standard +5°C adjustment would typically not be done. This exercise does highlight the extent that the mixing height changes given this adjustment.

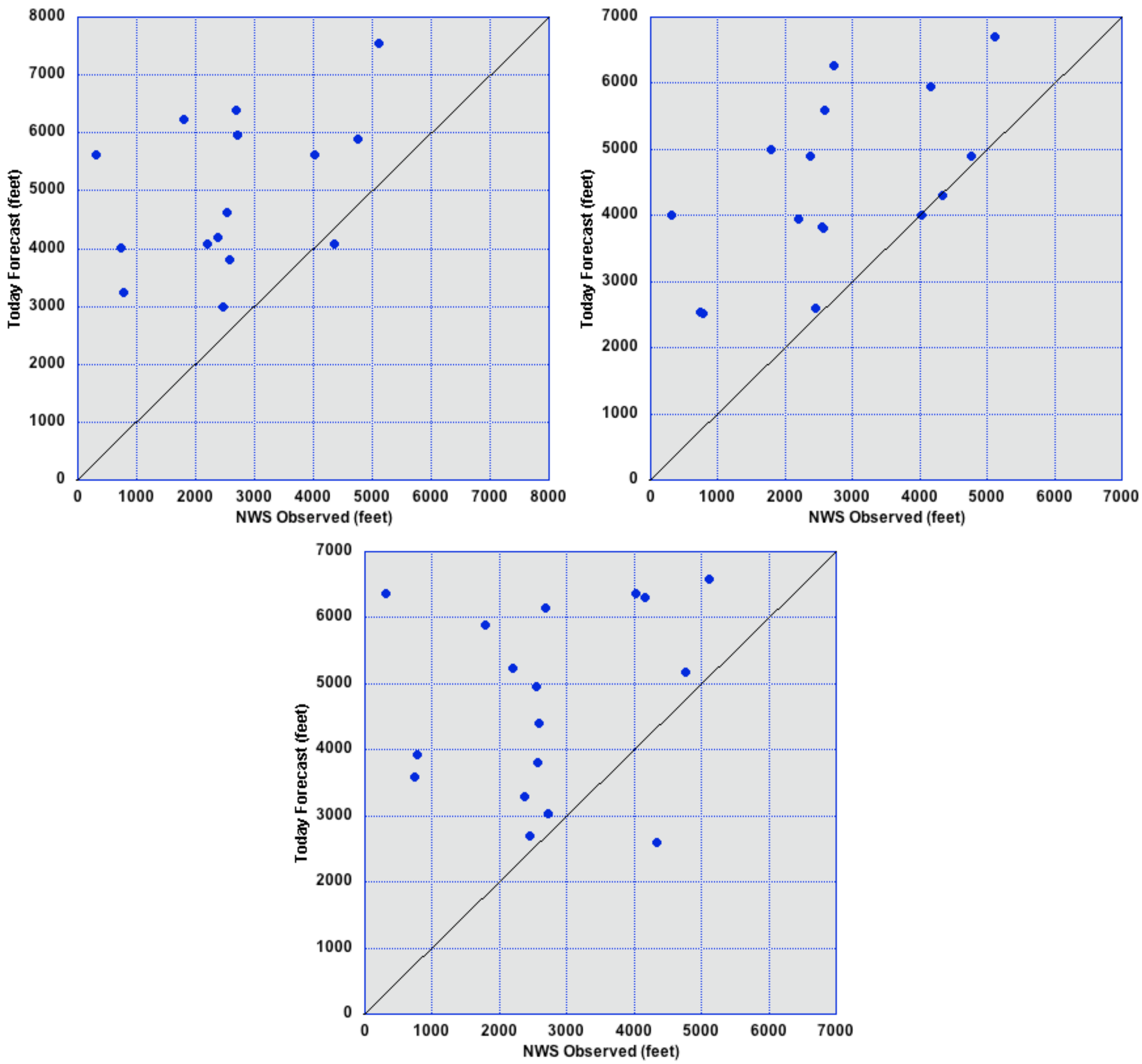

Figure 6. Scatterplots of NWS forecast versus NWS observed mixing heights.

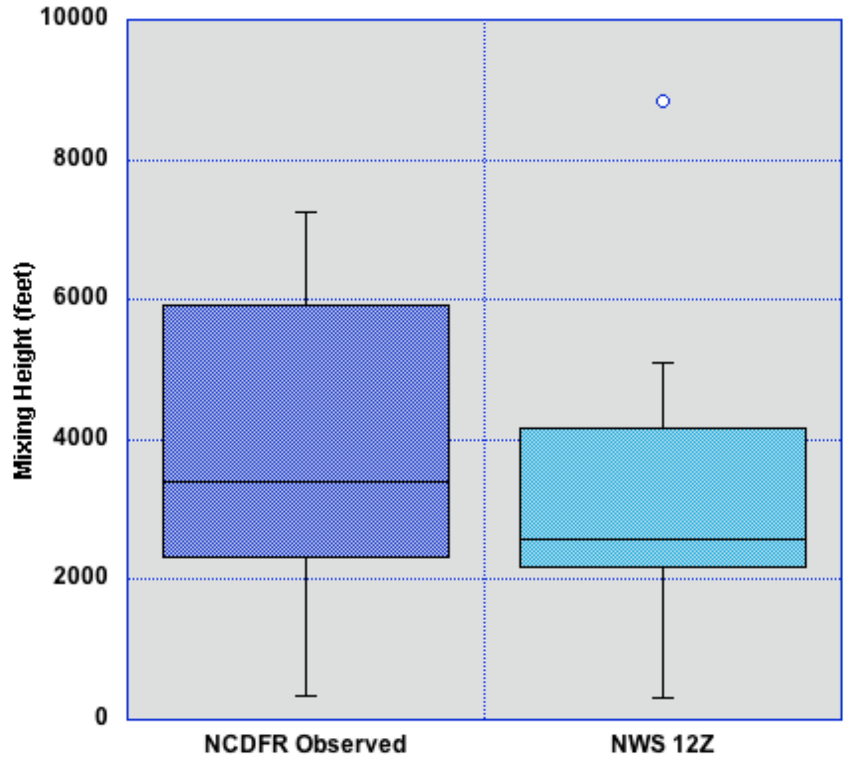

Figure 7. Boxplots of NCDFR and NWS 12 UTC observed mixing heights.

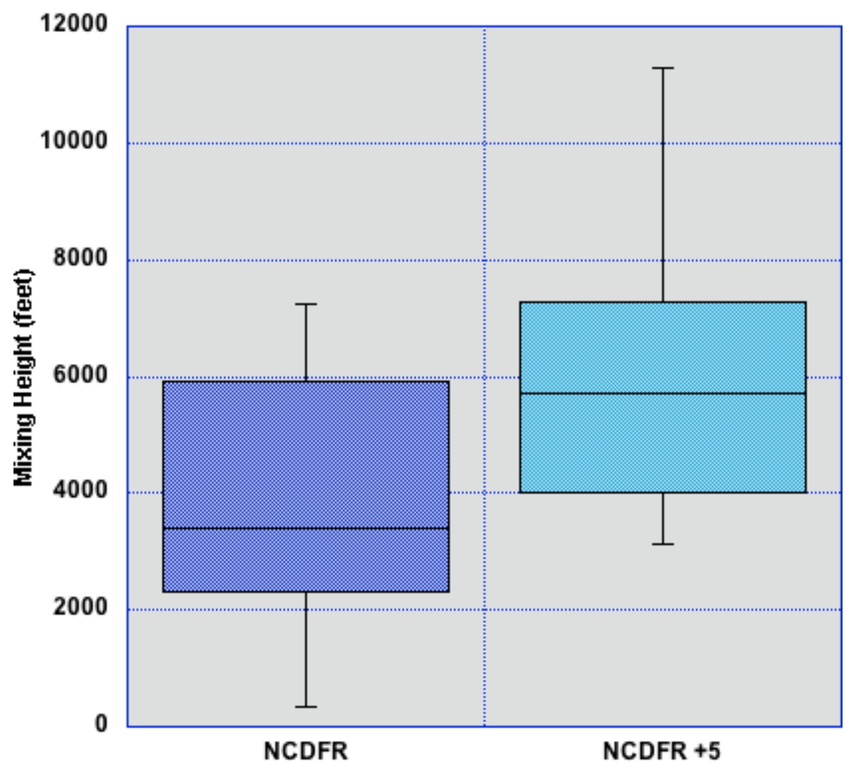

Figure 8. Boxplots of NCDFR mixing height using Holzworth method without and with a +5°C adjustment.

Fearon (2000) demonstrated that the Stull (1988) method of computing mixing height is more suitable for daily operations because it can yield more occurrences of higher mixing heights. This, for example, can be critical to fire management agencies conducting prescribing burning activities given limited resources and burn windows. The Stull method uses nonlocal static stability, which involves displacing parcels of virtual potential temperature upward from the relative maxima and downward from the relative minima where parcel movement is based on buoyancy measured by comparing the virtual potential temperature of the parcel to the environment at the same height. Ascent or descent of the parcel is tracked until it intersects the environmental profile or becomes neutrally buoyant. Once all parcel movements have been tracked for the entire profile, the static stability is then determined for each portion of the sounding domain. The mixing height is the top of the unstable layer after assessing nonlocal static stability. Figure 9 shows boxplots of the distributions of the NCDFR mixing heights for the unadjusted Holzworth and Stull methods. The full range of values for both methods is nearly the same, but mixing heights from the Stull method are generally higher. For example, the 25% percentile from Stull is nearly equivalent of the 50% percentile from Holzworth. Figure 10 shows a scatterplot of NCDFR Holzworth versus Stull values used in Figure 9. Seven of the 18 values match very closely between Holzworth and Stull. But for the majority of days, Stull values were higher than Holzworth. In two cases, Stull was substantially higher.

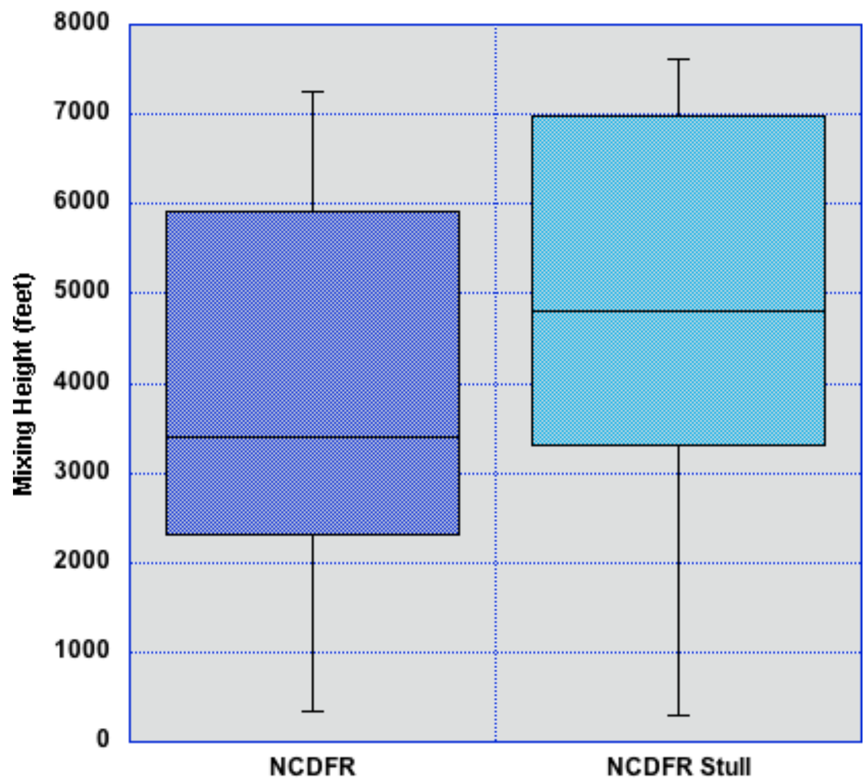

Figure 9. Boxplots of NCDFR mixing height using Holzworth method without an adjustment and the Stull method.

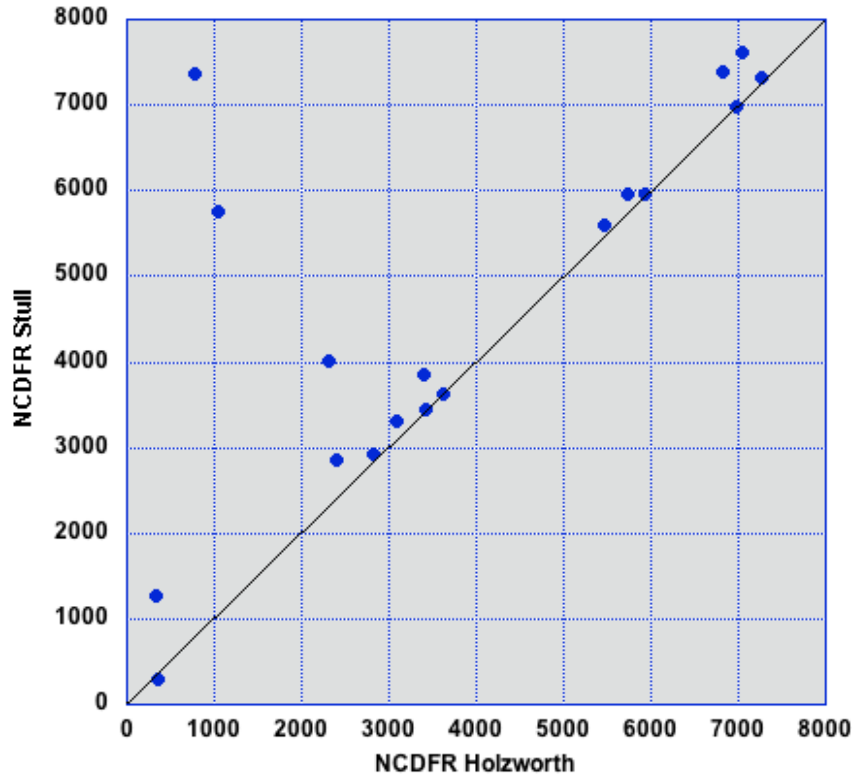

Figure 10. Scatterplot of NCDFR mixing height using Holzworth method without an adjustment and the Stull method.

Task element 3: Complete final report with results and recommendations and make a summary presentation.

Preliminary project results were presented at the March 2007 2nd Fire Behavior and Fuels Conference held in Destin, Florida. This report serves as the project final report.

4. Summary

The results of the project are summarized as follows:

- NWS forecasts from previous night and morning of the forecast day have generally high correlations with NCDFR soundings; the previous day forecast has a quite low correlation suggesting a more detailed issue than just the timing of the maximum mixing height.
- The NWS forecasts tend to have positive bias in that the forecast values are generally higher than observed. An important caveat of this result is that the mixing height observation does not necessarily coincide with the maximum mixing height of the day.
- The NWS forecasts in comparison to NWS soundings shows much lower correlations, and a much greater over-forecasting bias.

- Adding a +5°C adjustment to the Holzworth method for the afternoon NCDFR soundings not surprisingly created mixing height values that were too high.
- The Stull method for computing mixing height yielded generally higher values than Holzworth. From a previous study, it is argued that the Stull method yields truer mixing height values, and thus is preferred over Holzworth.

Acknowledgements

We very much thank Gary Curcio of the North Carolina Division of Forest Resources for the project funding support, data and guidance. Hauss Reinbold of DRI CEFA assisted with some of the sounding mixing height calculations. The North Carolina Division of Forest Resources funded this project.

References

Fearon, M., 2000: *The Use of Nonlocal Static Stability to Determine Mixing Height from NCEP Eta Model Output over the Western U.S.*, Masters Thesis, University of Nevada – Reno, 144 pp. Available at http://cefa.dri.edu/Publications/publications_home.php.

Holzworth, G.C., 1964: Estimates of mean maximum mixing depths in the contiguous United States. *Monthly Weather Review*, **92**, 235-242.

____ 1967: Mixing depths, wind speeds and air pollution potential for selected locations in the United States. *Journal of Applied Meteorology*, **6**, 1039-1044.

____ 1972: *Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States*, Meteorology Laboratory, EPA, Research Triangle Park, NC, 27711, 118 pp.

Stull, R.B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers, 666 pp.