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Impact of Increased Spatio-Temporal Radar Data Resolution on Forecaster Wind Assessments

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***Abstract*— This study examines the impact of increased spatio-temporal resolution weather radar data on the judgment accuracy and warning decisions of forecasters. In a static part-task setting, weather forecasters were provided with high resolution radar data in addition to conventional radar data and asked to forecast ground level winds two to five minutes into the future. When given these additional data, subjects significantly increased wind speed assessments, decreased absolute error, increased confidence ratings, and changed the number of affirmative warning decisions.**

***Keywords*—decision making, weather forecasting, weather radar, wind speed, human judgment**

I. Introduction

Severe weather threatens lives and property. Losses from weather hazards such as hail, high winds, flooding, and tornadoes can be reduced if the public is given sufficient warning to take protective action. Forecasters use remote sensor systems – such as radar, satellite, and ground sensors – to forecast hazards, assess existing hazards, and to issue and cancel related weather warnings. In the United States, the National Weather Service (NWS) operates 159 Doppler weather radars called WSR-88D or NEXRAD [1] in order to supply data including reflectivity (which relates to precipitation rate) and velocity (which indicates radial wind speed). When operating in a severe storm environment, NEXRAD radars generally perform a complete multiple-tilt scan every 4-5 minutes with a spatial resolution of 0.54-2.16 nmi [1]. These radars generate reflectivity and velocity products out to 124 nmi in range but have limited coverage below 6,500 ft AGL (above ground level) [2].

NWS forecasters make weather hazard assessments and decisions using weather products and procedures that help them to maintain a "big picture" awareness, to build conceptual models, and to update them with small scale details from radar product interpretation [3]. Forecasters primarily rely on NEXRAD Doppler radar products for real-time weather hazard assessment [3,4]. For example, a forecaster can determine whether a storm is severe based solely on radar products. A storm is considered severe when at least one of three conditions is met: surface wind gusts exceed 50 knots (determined via interpreting and integrating velocity data), hail exceeds ¾ inch diameter (determined via interpreting and integrating reflectivity data), or tornado production (determined via interpreting and integrating reflectivity and velocity data plus developing a mental picture of storm structure and evolution) [5].

Unfortunately, using radar to assess weather hazards such as severe surface winds can be challenging because of inherent limitations in data availability and precision. The data are not available uniformly in space and, in some cases, not at all. Under ideal conditions radar beams travel in a straight line which limits the coverage area of radar systems to objects on their horizon due to the curvature of the Earth. Radar beams are pointed at angles (tilts) above the horizon; therefore the atmosphere low to the ground and far from the radar is not sampled. The radar beam spreads out as it travels, resulting in lower spatial resolution with increased distance from the radar. With respect to velocity, Doppler radars can only detect wind speed by the motion of water droplets or other airborne objects moving parallel to the radar beams. Thus velocity data show radial wind speed, i.e. towards and away from the radar along the radar beam. Winds traveling perpendicular to the radar beam are not detected.

Technological advances, new approaches to radar design and deployment, and new data dissemination techniques could enhance the warning process by providing more data that are also more accurate. For example, increases in processing power should allow for more effective signal processing which can create high quality data with lower cost transmitters. Also, phased-array antenna technology creates electronically directed beams with little or no moving parts allowing for faster scanning and therefore higher data update rates. Smaller antenna designs and low cost transmitters can allow for multiple radar nodes to overlap coverage of an area, thereby helping to fill gaps in coverage and determine true wind velocities.

There are both quantitative and qualitative impacts of such advances. While they have the potential to improve the weather hazard assessment and warning process, their exact impacts should be quantified in order to influence training, decision support tool design, normative decision making processes and policy. With respect to resolution, for example, Brown and Wood [6] indicate that radars with greater spatial resolution will report radial wind velocities with greater (absolute) magnitudes and will therefore depict severe storm signatures more clearly than their lower resolution counterparts. These sampling changes can lead to higher forecaster wind speed assessments and differences in the number of wind-related warnings. Thus any analysis of new radar systems should investigate the quantitative impact of improved design features such as spatial resolution on the task or sub-tasks of warning decision making.

To evaluate the impact on the forecaster decision making process, quantitative outcome and process measures should be considered. For example, to evaluate hazard assessments, judgments can be compared to ground truth where available. Qualitative measures, such as confidence [7] can also provide insight into how data are affecting a forecaster's decision process.

The Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) is creating a new paradigm for radar systems based on dense networks of low-cost X-Band radars [8]. CASA radars are designed with a shorter range than NEXRAD and they can be deployed with overlapping regions of coverage. These technological changes result in increased spatial resolution (median 0.27 nmi versus 1.35 nmi), temporal resolution (update rates of 60 seconds versus 4-5 minutes), and lower elevation coverage (floor 330 ft [8]) when compared to NEXRAD. In addition, to address changes related to velocity determination, radars can be deployed closer together, thereby creating conditions where multiple radars can scan the same portion of the atmosphere. The dense network of sensors concept from CASA increases the opportunity for a variety of wind-to-beam intersection angles, further improving velocity detections.

CASA is currently operating a four node radar test bed in south-west Oklahoma [8]. By design, data from this test bed can be described as "more relevant" and "high quality", attributes predicted to increase accuracy and reliability (or consistency) in forecasts [9]. Also, the data contain additional cues – such as very small scale rotations and strong low-level winds [10] – that are important to severe thunderstorm warnings.

The study described herein measures the impact of the addition of CASA radar data (with its greater temporal and spatial resolution) on forecasters' wind speed assessment and warning decisions. In a static part-task setting using a case review paradigm, impacts are measured via forecaster accuracy, magnitude of the wind assessment, forecaster confidence, and the number of warning decisions. We hypothesize that, when these CASA data are provided, surface wind speed assessments will be greater, assessment error will be lower, and forecaster confidence will be higher. Further, we hypothesize that due to higher wind speed assessments, there will be more affirmative decisions to issue warnings.

II. Methods

A. *Participants*

Sixteen people (12 male, 4 female) with operational NWS forecasting experience ranging from 5 to 25 years (M=14.4 years, SD=5.9) participated in the experiment. Forecasters were recruited using posters and verbal announcements at the 33rd Annual meeting of the National Weather Association (NWA) that took place in Louisville, KY, October 11-16, 2008.

B. *Apparatus and Materials*

Workstation. Five identical workstations were placed in a dedicated room at the annual meeting hotel. Each HP® brand desktop workstation was running Ubuntu® Linux® 64-bit on an Intel® Core™ 2 Duo 2.0GHz CPU with 3GB RAM and an 80GB hard drive. An NVIDIA® GeForce® 8400-GS based video card was used for OpenGL® acceleration with a common 19-inch LCD monitor running at 1280x1024 pixel resolution. In addition to a standard mouse and keyboard, each workstation was equipped with a small microphone for audio recording.

Display and Data Collection Software. WDSS-II [11] display software was used to render CASA and NEXRAD data in a case-review mode, i.e. no forced advancement of the simulated clock. The WDSS-II display window was maximized with the control widgets hidden providing approximately 154 in^2 of display surface for radar data (Fig. 1). The WDSS-II default color tables were adjusted to "black out" velocity data in the -5 to 5 kt range, an ambiguous range for CASA sources. This custom color table was used for both CASA and NEXRAD radial velocity products. Desktop visuals, mouse movements, and audio recordings were captured by "recordMyDesktop" [12], an open source software package.

Custom software was created to generate all required WDSS-II data indices and configuration files and to automate the experimental procedure. Shell scripts initialized each experimental task and started the desktop and audio recording package prior to launching the WDSS-II radar display.

Weather Scenarios. The experimental task was to assess radar data and to predict wind speed at the ground, 2 to 5 minutes into the future at a specified location. Weather radar data used in this experiment were selected from the corpus archived as part of CASA operations in 2008 [13]. In order to reduce forecaster efforts of relearning different synoptic scale situations, 6 approximately 12 minute long scenarios were chosen from the same day (May 7, 2008). These scenarios had similar but discrete storm cells producing straight line winds in the 20-50 kt range and adequate CASA and NEXRAD coverage.

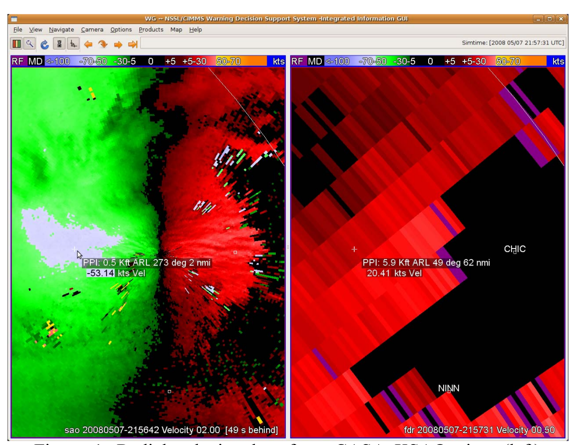

Figure 1. Radial velocity data from CASA KSAO view (left) and NEXRAD KFDR view (right) for scenario 5. NINN and CHIC markers are OK Mesonet ground based sensors.

Both reflectivity and radial velocity data were provided from each radar with matching time windows for each scenario. No forecast data were provided. NEXRAD Level-II data from Frederick, OK (KFDR) were available at 14 standard tilts in the 0.5° to 19.5° range (a storm mode called "VCP 12"). CASA data from all 4 radar nodes (KCYR, KLWE, KRSP, KSAO) were available at 7 tilts: 1°, 2°, 3°, 5°, 9°, 11°, 14°. All CASA radars provide a full (360° azimuth) scan at the 2° tilt, other tilts were dynamically configured partial sectors [13].

Ground sensor readings from the Oklahoma Mesonet (which provides data from a variety of sensors every 5 minutes [14]) provided the ground truth criterion. The criterion was WMAX, defined as "the maximum (or peak) 3 s wind speed observed during a 5-minute interval at a height of 10 meters above ground" [15].

Scenario 1 had a small and moderate strength, poorly organized, storm cell pass over the targeted mesonet site. CASA data showed radial velocities in the mid 40 kt range but not directly adjacent to the target. Scenario 2 involved a broader storm cell that included high radial velocities (50-55 kt) that were near the target (to the south-southeast). Scenario 3 included 50-60 kt radial velocities in both radar sources that came within a 2-3 miles of the target. Scenario 4 included a storm cell that had no obviously high radial velocities at the target (KFDR had a large area of 0-5 kt radial velocities adjacent to the target which were filtered out). Scenario 5 had a similar low velocity area near the target in KFDR data but CASA data included velocities in the low 50 kt range very close to the radar (i.e., at a very low elevation). Scenario 6 showed a cell as it approached the eastern edge of CASA radar coverage that included a small, but possibly strengthening, area of winds over 50 kt. The KFDR view included a few gates (pixels) of data in this range, but not with the continuity shown in CASA data.

C. *Independent Variables*

Weather Scenario. There were six weather scenarios. Participants saw them in their natural (time ordered) sequence. Each weather scenario contained different characteristics such as wind-to-beam intersection angle, distance from the specified location to the radar, and the last displayed radial velocity data value.

Table I provides the criterion of each scenario, the maximum wind speed value for the two data sources near the criterion's location, and the difference between each source and the criterion. The data source local maximum values were determined from a small area around the Mesonet site. These scenarios yielded a lower average local maximum for the CASA data (27.5 kt) as compared to NEXRAD (32.3 kt). The CASA data had larger differences than the NEXRAD ones as the total of and the absolute value of the differences for all weather scenarios were -64 kt and 94 kt for the CASA data source while only -35 kt and 53 kt for NEXRAD.

Some interaction between task-set and data source can be expected due to natural variations in the scenarios and alternating data source across participants. These values can be seen in the "local max" values of Table I and in the task set description. For local max across the four combinations of task set and data source, N-first CASA has the lowest wind speeds (mean 18 kt) and the greatest difference to the criterion (mean of absolute values, 24 kt) whereas N-first NEXRAD has the highest wind speeds (mean 39 kt) and the smallest criterion difference (mean of absolute values, 7 kt).

Table I. Local maximum wind speed and criterion comparison for 6 scenarios (kt)

Scen.	Criterion	NEXRAD local max	Criterion NEXRAD Difference	CASA local max	Criterion CASA Difference
1	32.1	41	+8.9	18	-14.1
2	22.5	13	-9.5	32	+9.5
3	42.8	40	-2.8	40	-2.8
4	34.6	26	-8.6	9	-25.6
5	46.7	37	-9.7	52	5.3
6	50.7	37	-13.7	14	-36.7
Mean		32.3	-5.9	27.5	-10.7
Abs. Total			53.2		94.0

Data Source. Participants either saw weather scenarios with only NEXRAD data or both CASA and NEXRAD data. Data source indicates if radar data were supplied from "NEXRAD only" (N) or "CASA & NEXRAD" (C).

Task Set. Participants either saw the first scenario with NEXRAD only data or CASA and NEXRAD data. For all participants, the remaining tasks alternated between data sources. Task set refers to the assignment of data source alternations. Task sets were either {C,N,C,N,C,N} for "C-first" or {N,C,N,C,N,C} for "N-first".

The N-first task set was inherently harder than the C-first task set based on the difference between the source data "local maximum" and the criterion. The N-first task set had a larger total difference than the C-First task set (-56.4 vs. -43.4 kt). For the three scenarios with CASA data in the N-first task set, the sum of the differences and the absolute value differences between the CASA local maximum and the criterion were -52.8 kt and 71.8 kt and for the three NEXRAD only scenarios, -3.6 kt and 21.4 kt yielding total differences of -56.4 kt and 93.2 kt. For the C-first task set, the sums of the differences and absolute value differences between the CASA local maximum for the three scenarios were -11.6 kt and 22.2 kt and those with NEXRAD only data using the NEXRAD local maximum were -31.8 kt and 31.8 kt, yielding totals of -43.4 kt and 54 kt.

D. *Dependent Variables*

Wind Speed Assessment. Wind speed assessment is the ground level wind speed (forecasted) for the target location by the participant to the nearest 1 knot. Most participants responded with a single integer value. When participants provided a range, the response was recoded as the mean of the range (e.g. 45-50 kt was recoded as 48 kt).

Absolute Wind Speed Assessment Error. The error is the absolute value of the difference between the wind speed assessment and the automated ground sensor reading rounded to the nearest 1 knot.

Assessment Confidence. After providing their wind speed assessment participants were asked "how confident are you in this estimate" on a scale from 1-"Not Confident" to 7-"Very Confident". Responses marked between numbers on the scale were recorded as the lower integer.

Warning Decision. After providing their confidence rating participants were asked "do these radar based winds indicate a warning is needed" and a "Yes" or "No" response was recorded. Responses that did not include the exact term "Yes" or "No" were interpreted by the first author and recoded as "Yes", "No", or "Missing".

E. Procedure

Each experimental session lasted approximately 90 minutes. Participants first received background information about the CASA organization and the 4 node radar test bed. This background consisted of a brief lecture, including slides, followed by a demonstration of CASA and NEXRAD data. After reading and signing the informed consent, participants then completed a demographics questionnaire. Prior to working with data on the workstation, participants were given a packet of printed weather products to provide appropriate background information.

The participants were provided a step-by-step guide to selecting, navigating, and viewing data using the WDSS-II display. Operating the WDSS-II radar display tool required operations such as panning and zooming the data sources, using cursor value readouts, switching between radar sources or products, and stepping through the time-stamped products. They practiced with the display system for as long as they wanted.

Using these instructions, each participant completed one training weather scenario. Each used the mouse or keyboard commands to view various reflectivity and radial velocity data time-stamped products at different tilts. Each participant recorded the wind speed assessment, confidence rating, and warning decision. The automated ground sensor reading was then provided as feedback.

After the training, each participant then began the 6 experimental tasks which were similar to the training task but without guided instructions. At the beginning of each task, participants were asked to limit their radar interrogation to "about 12 minutes" in order to represent the pressure of real-time events. However, no time limits were strictly enforced. When WDSS-II was launched for a task, the desktop and audio recording started. Participants interrogated the data, wrote their wind assessment, confidence rating, and warning decision. After completing the task, they were shown the automated ground sensor reading (the criterion).

F. Experimental Design and Data Analysis

This study was a repeated-measures design with task-set as the within-subjects factor and data source as the between-subjects factor. The experiment collected 3 replicates from each participant under each of the 2 between-subjects conditions. Eight participants saw the C-first task set and the other eight the N-first task set. All completed the entire experiment yielding 96 individual wind speed assessments.

Data source and task set effects on the wind speed assessment and the absolute wind speed assessment error were analyzed using a repeated measures analysis of variance. Data source and task set effects on confidence were analyzed using Friedman tests. Data source effects on warning decisions were analyzed using a Pearson's chi-square test.

III. RESULTS

Results are reported as significant for $\alpha=0.05$. Post-hoc power calculations were computed using G*Power [16].

A. Wind Speed Assessment

The main effect of the data source on wind speed assessments was significant ($F_{1,28}=15.3$, p=0.001) with power (1-ß)=0.97. Mean wind speed assessment with both data sources was 40.1 kt whereas NEXRAD only was 33.9 kt (Fig. 2). The main effect of task set was not significant. The data source-task set interaction was significant ($F_{1,28}=16.3$, $p<0.001$). This interaction shows little change for the N-first task set across data sources (38.0 kt for N and 37.8 kt for C), and a large change across data sources for the C-first task set (29.9 kt for the NEXRAD data source and 42.5 kt for the scenarios with both sources). The highest wind speed assessments occur with the C-first task set with CASA and NEXRAD data.

B. Absolute Wind Speed Assessment Error

The effect of data source on assessment error is significant ($F_{1,28}=7.3$, p=0.012) with power (1-ß)=0.74. Mean assessment error with both data sources was 7.9 kt whereas NEXRAD only was 11.5 kt (Fig. 3). The main effect of task set was significant ($F_{1,28}=4.4$, p=0.045). Mean assessment error for the C-first task set was 8.3 kt whereas N-first was 11.1 kt. The data source-task set interaction was significant ($F_{1,28}=9.3$, p=0.005). This interaction shows little change for the N-first task set across data sources (10.9 kt for NEXRAD only and 11.3 for scenarios with both sources), and a large change across data sources for the C-first task set (12.1 for the NEXRAD data source and 4.4 for scenarios with both sources). The lowest error occurs with the C-first task set with CASA and NEXRAD data.

C. Assessment Confidence

Assessment confidence varied significantly between data sources ($\chi^{2}=16.0$, df=1, $p<0.001$). The mode with CASA and NEXRAD data sources was 5 whereas NEXRAD only was 4 (Fig. 4). Assessment confidence did not vary significantly between task sets.

D. Warning Decision

Data source had a significant effect on the proportion of Yes/No warning decisions ($\chi^{2}=7.3$, df=1, p=0.007). Warning decisions with CASA and NEXRAD were 30 of 47 "No" responses whereas with NEXRAD only 42 of 48 "No" responses (Fig. 5). One response consisted of an ambiguous response and was removed.

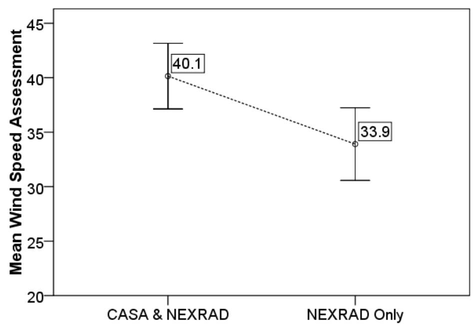

Figure 2. Mean and 95% confidence interval for wind speed assessment as a function of data source

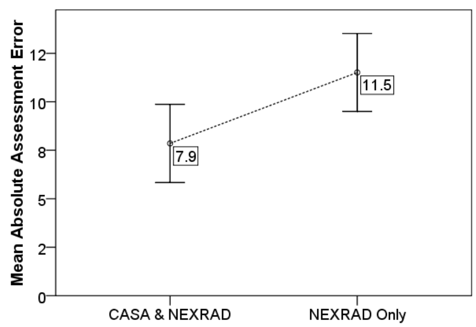

Figure 3. Mean and 95% confidence interval for absolute wind speed assessment error as a function of data source

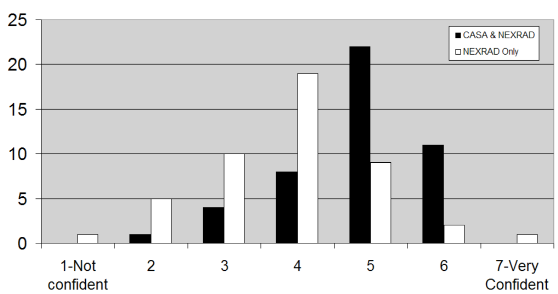

Figure 4. Histogram of confidence by data source

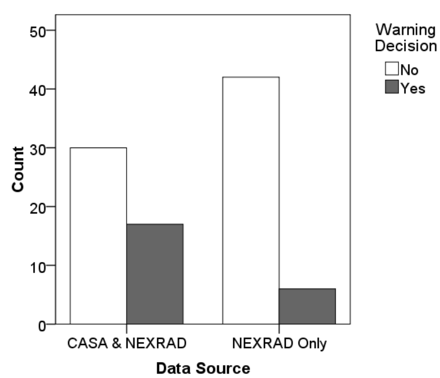

Figure 5. Response counts for warning decision

Two weather scenarios in particular had notable warning responses. The 4th scenario had complete agreement across data sources whereas the 5th scenario had complete disagreement. Scenario 5 with NEXRAD only had all "No" responses (8) whereas CASA and NEXRAD had all "Yes" responses (7) and one missing response.

IV. Discussion

Because wind speed plays a critical role in severe thunderstorm warnings, the purpose of this study was to measure the impact of the addition of high resolution radar data on wind speed assessments. Operational forecasters were asked to make wind assessments under two data source conditions, NEXRAD only and NEXRAD and CASA. The results show that forecasters who are provided CASA radar data significantly increased wind speed estimates, reduced assessment error, and increased confidence for wind speed assessments. In addition 11 of 16 participants provided written feedback that the CASA data confirmed their mental models of the atmosphere. It is very promising that forecasters with minimal training were able to effectively integrate data from an experimental radar system which does not have the same noise level and performance characteristic of a production NEXRAD.

The increase in mean wind speed assessments, for forecasters using both NEXRAD and CASA data sources, lends support to work by Brown and Wood [6] who predict that increased spatial sampling results in higher radial velocity data points. These higher values in the CASA data were visible in the display and observable by the forecasters resulting in wind speed assessments higher than with only NEXRAD data. The mean of local max values (across all scenarios) for the CASA source is 27.5 kt, whereas NEXRAD is 32 kt. This shows that the forecasters did more than report the last display value at the target location (otherwise wind speeds should have been lower when given CASA data). Forecasters may have been looking at data values further away from the target to compensate for storm motion and the 2-5 minute forecast period.

These higher estimates were closer to the ground truth obtained from automated sensors, resulting in lower mean error. The results show forecasters were able to reduce their wind speed assessment error using this additional data source. This implies that forecasters are able to sift through the extra data points from increased spatial resolution, and find the data that are the most informative to their mental model.

The shift in warning decisions across all scenarios, from 88% "No" with NEXRAD only to 64% "No" with NEXRAD and CASA data, is interesting, especially because only one scenario (the 2nd) was covered by an actual warning according to NWS archives. This shift may be related to the increase in wind speed assessments when given CASA data which are based on the higher radial velocity values in the display. Since most scenarios had near but sub-severe winds it seems appropriate that some but not all warning decisions were altered. This implies the new data supported both negative and affirmative warning decisions.

Forecasters were revealing a confidence in their higher speed estimates both in their higher confidence ratings and their shift to more warning decisions. This has an implication for operational forecasters who will need to adapt their mental models given these higher estimates. As systems such as CASA, NEXRAD "Super Resolution" [17], and MPAR [18] come on-line, the forecast community may need to revisit the policies and thresholds for issuing warnings.

The current study could be enhanced by the systematic control of radar beam attributes. Update rate, beam height, wind-to-beam intersection angle, and sampling fidelity each influence performance. Future work could quantify the impact of these attributes individually. To fully understand the impact on warnings additional measures of performance will need to be collected including the size of warnings, their duration, and effective lead time.

WDSS-II, while an effective tool, would ideally be replaced by standard NWS operations software to remove additional confounds and allow detailed warning generation. This standard software, called AWIPS, provides data from many sensors in real time, allowing forecasters to quickly interrogate them visually and with built-in tools [19]. Experienced forecasters have strongly developed motor and cognitive routines for accessing radar data in an orderly fashion to build their mental model of the storm. However, the interface control differences between the WDSS-II [11] software used and AWIPS [19] interfered with these routines. Further radar rendering and display differences may have caused additional error in interpretation due to coloring or other visual differences. Future integration of CASA data into AWIPS would alleviate these issues and provide additional data sources (e.g. satellites) normally available during operations. This integration would allow for even more realistic test settings and possible reductions in assessment error.

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