ASSESSMENT OF THE MULTI-RADAR/MULTI-SENSOR SYSTEM (MRMS) AND THE CORRIDOR INTEGRATED WEATHER SYSTEM (CIWS)

Prepared by

NOAA/ESRL/GSD/Forecast Impact and Quality Assessment Section

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EXECUTIVE SUMMARY

The Forecast Impact and Quality Assessment Section of NOAA/ESRL/GSD was tasked to perform an assessment of the Multi-Radar/Multi-Sensor system (MRMS) developed by the NOAA National Severe Storms Laboratory (NSSL) and the Corridor Integrated Weather System (CIWS) developed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory (LL). These products both provide an analysis and short-term (2-hour) forecast of radar-derived fields, namely, Vertically Integrated Liquid (VIL) and height of the 18 dBZ surface (Echo Top, ET).

The assessment incorporates output from the MRMS and CIWS algorithms, as well as observations (including radar, satellite, METAR, and sounding data), in order to identify similarities and differences between MRMS and CIWS products; establish a baseline for analysis/forecast characteristics, including differences between the two products; and evaluate results to support future incorporation of MRMS into tools and assessments.

Findings are based upon data assessed over the period of Dec 2013 – May 2014 in order to utilize the latest version of MRMS that included the incorporation of dual pol radar (introduced Sept 2013). A comparison between May 2013 and May 2014 data was also performed to try to determine what, if any, the incorporation of dual pol might have had on the MRMS product.

The providing data centers for the assessment data were the FAA William J. Hughes Technical Center for MRMS data, and MIT/LL for CIWS data. Note that a cursory look at MRMS as produced by NSSL (Appendix A) reveals differences between it and FAA Tech Center version of MRMS. These types of differences could also exist between the operational version of MRMS (transitioned from NSSL to run operationally at NCEP) and the FAA Tech Center version.

Primary findings include:

Dec 2013 – May 2014:

- CIWS generally has a greater VIL extent and intensity than MRMS
- CIWS Echo Top appears to give a more accurate representation than MRMS
    - MRMS Echo Top is higher than CIWS, and has some unexpectedly high ET values
- Case studies indicate that the CIWS ET and VIL fields offer a more conservative view of hazardous convection with regard to any potentially high VIL (e.g., CIWS identifies more hazardous convection, restricting the airspace more than MRMS), as compared to individual radar observations than those of MRMS
- The similarity between forecast and corresponding analysis is roughly equivalent at the 30 min lead for MRMS and CIWS; CIWS forecasts are generally closer to their analyses than MRMS forecasts are to their analyses for leads > 30 minutes
- In comparison to METAR reports

- When considering a VIL threshold of 0 kg/m^3, MRMS is more consistent with METAR reports than CIWS is.
- When considering a VIL threshold of 0.14 kg/m^3 (VIP level 1), CIWS forecasts are more consistent with METAR reports than MRMS forecasts are.
- When considering a VIL threshold of 0.14 kg/m^3 (VIP level 1), MRMS analyses are more consistent with reports of clear skies than CIWS—MRMS has fewer cases of VIL when METAR reports clear skies

May 2013 vs May 2014

- There is a decrease in MRMS high VIL values from 2013 to 2014, whereas CIWS distributions remain very similar, indicating effects of the introduction of dual pol
- Relative differences from MRMS to CIWS seem to be consistent between 2013 and 2014—MRMS has fewer non-zero VIL pixels than CIWS, and a greater number of high (greater than 50,000 feet) echo tops values, in both years.

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1 INTRODUCTION

The Forecast Impact and Quality Assessment Section was tasked with an assessment of the Multi-Radar/Multi-Sensor system (MRMS) developed by the NOAA National Severe Storms Laboratory (NSSL) and the Corridor Integrated Weather System (CIWS) developed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory (LL). These products both provide an analysis and short-term (2-hour) forecast of radar-derived fields, namely, Vertically Integrated Liquid (VIL) and height of the 18 dBZ surface (Echo Top, ET).

The assessment incorporates output from the MRMS and CIWS algorithms, as well as observations (including radar, satellite, METAR, and sounding data), in order to identify similarities and differences between MRMS and CIWS products; establish a baseline for analysis/forecast characteristics, including differences between the two products; and evaluate results to support future incorporation of MRMS into tools and assessments. The assessment addresses five main areas of investigation summarized below.

Quantitative areas of investigation:

1. Evaluation of field characteristics of each product (forecast and analysis)
2. Evaluation of consistency within the analysis and forecast leads of each product (intra-model comparison)
3. Assessment of forecast products in comparison to analyses (intra- and inter-comparisons) using the following approaches:
    a. Pixel to Pixel
    b. Fractions Skill Score (FSS)
    c. Flow Constraint Index (FCI)
4. Evaluation of correspondence of each product with other observational sets (METARs)

Qualitative areas of investigation:

5. Case study analysis of each analysis product

The results and conclusions obtained from this assessment aim to provide information to NWS management regarding the differences between the MRMS and CIWS products in their representation of convection.

2 DATA

This section describes the forecast and observation data that will be included in the assessment, along with the principal stratifications to be used. The primary time period for this study is approximately six months, December 2013 – May 2014. In addition, data from May 2013 (prior to the incorporation of dual-pol radar data into MRMS) is investigated. CIWS data was provided by MIT/LL for this assessment, while MRMS data was ingested via a feed from the Federal Aviation Administration (FAA) William J. Hughes Technical Center, as this was considered the operational feed. Note that a cursory look at MRMS as produced by NSSL reveals differences between it and the

FAA Tech Center version of MRMS (Appendix A). These types of differences could also exist between the operational version of MRMS (transitioned from NSSL to run operationally at NCEP) and the FAA Tech Center version.

2.1 CIWS AND MRMS ANALYSES/FORECASTS

The output from the grid-based MRMS and CIWS algorithms is vertically integrated liquid (VIL), in units of kilograms per square meter, and the height of the 18 dBZ surface, known as echo top (ET), in units of ft. The methodology used for producing the MRMS mosaic can be found in Langston et al. (2007), while information on the individual products is available from (WDTB 2014). References for CIWS methodologies can be found in Evans and Ducot (2006). The major difference in the VIL algorithms is understood to be as follows: for MRMS, the radar information is mosaicked first, then VIL is computed; for CIWS, VIL is first derived for each radar, then the maximum 'plausible' VIL value is used for each pixel. The spatial and temporal attributes of the MRMS and CIWS, as used in this assessment, are outlined in Table 2.1.

Issues	CIWS: Every 30 minutes MRMS: Roughly every 30 minutes (use "Price is Right" rule – closest without going over 15 minute mark)
Leads	0, 30, 60, 90, and 120 minutes
Horizontal Resolution	CIWS: 1km MRMS: 0.01-degree
Altitudes	CIWS: 500-75,000 ft, 500 ft increments MRMS: 0.5-19.5 km, 0.5 km increments

TABLE 2.1: ATTRIBUTES OF THE CIWS/MRMS.

2.2 OBSERVATIONS

2.2.1 RADAR

The CIWS and MRMS products are mosaics of individual NEXRAD radar information. NEXRAD Level-III VIL data at multiple overlapping radar locations (KSRX, KSGF, KLZK, KSHV), obtained from the National Climate Data Center (NCDC) website, are utilized in case studies to quantitatively assess the CIWS and MRMS mosaic algorithms.

2.2.2 METAR OBSERVATIONS

Routine surface report (METAR) data provide observations of rainfall and cloud cover, which are used to define an expectation of non-zero VIL and ET at a location. When rain is recorded in the METAR, the VIL and ET values in the MRMS and CIWS products should be greater than zero at that location; when the METAR records no rain, CIWS and MRMS are likely to have low VIL values. The METAR observations are also used in the case studies to compare the present weather (thunderstorms or clear skies) to the VIL and ET fields in the vicinity of the METAR location.

2.2.3 SOUNDING DATA

Balloon-borne instruments, launched twice daily at various locations around the United States, provide vertical profiles of temperature and moisture. When combined with satellite estimates of cloud-top temperatures, the sounding data provide an estimate of echo top height.

2.2.4 GOES SATELLITE

Infrared satellite imagery provides an estimate of cloud top temperature, which, when combined with information from a sounding, can provide an estimate of cloud top height. As mentioned above, the cloud-top height can serve as an estimate of ET height. (Note, it is not expected that the satellite-based cloud top height and radar-based ET height should match exactly. Rather the cloud-top height should be a reasonable approximation of the ET height.)

2.3 STRATIFICATIONS

Performance results are stratified spatially and temporally as specified below.

GEOGRAPHICAL STRATIFICATIONS

The product domains are divided into four regions (West, Central, Northeast, and Southeast), as defined in Figure 2.1.

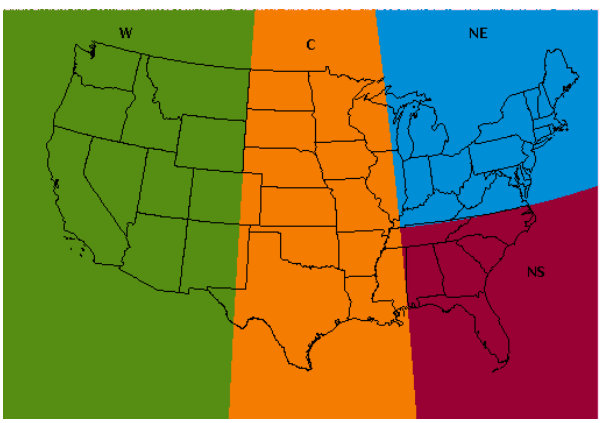


FIGURE 2.1 MAP OF THE GEOGRAPHIC REGIONS.

TEMPORAL STRATIFICATION

Forecast performance is stratified by forecast issue time and lead time.

THRESHOLD STRATIFICATION

Five VIL thresholds are used: 0, 0.14, 0.76, 3.5, and 6.9 kg/m^2, which correspond to VIP levels 0-4.

While several ET thresholds were examined, only the 0 and 20,000 ft thresholds are included for the results shown herein.

3 METHODS

A variety of verification approaches, outlined in the Introduction, are employed in this assessment and described in detail in the following subsections.

3.1 MRMS and CIWS Field Characteristics

An investigation of MRMS and CIWS field characteristics in forecast and analysis products is used to identify discrepancies and trends in the VIL and ET fields.

3.1.1 Climatological Maps

Climatological maps are constructed from aggregate counts of field values exceeding a threshold (e.g., VIL ≥ 3.5 kg/m^2 and ET ≥ 20,000 ft) at each pixel over a specific period and set of issue/leads. These geographical representations are used to determine general geographical tendencies.

3.1.2 Field Value Distributions

By binning field values and summing the total number of data points in each bin, one can evaluate the frequency of occurrence of VIL and ET values. Distributions are computed for VIL and ET independently and in combination (e.g., ET where VIL ≥ 3.5 kg/m^2).

3.2 MRMS and CIWS Intra-Model Consistency

In this area of investigation, the intra-model consistency for both MRMS and CIWS is assessed. For each product, the similarity is calculated between forecasts of consecutive lead-times to identify systematic changes in the fields at particular leads that may be jarring to a forecast user. The measure of similarity used is the CSI, which is the ratio of the intersection of two fields to the union of those fields.

Within each product, the 120-minute forecast is compared to the 90-minute forecast valid at the same time. Similar comparisons of the 90 to 60-minute, 60 to 30-minute, and 30-minute to analysis are performed. Additionally, each lead-time is compared to the analysis valid at the same time. Consistency is calculated for VIL fields of any ET for the 0.76 and 3.5 kg/m^2 VIL thresholds.

This type of comparison can be used as a baseline correlation measure for each product.

3.3 MRMS and CIWS Forecast Comparison to MRMS and CIWS Analyses

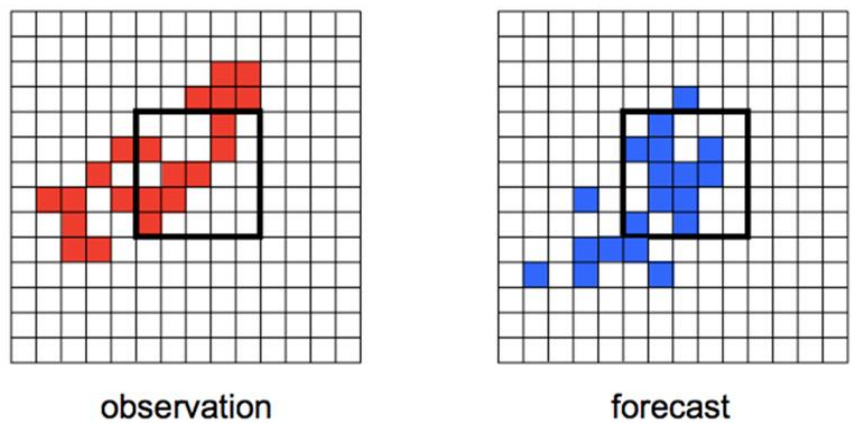
Three methods are employed to compare forecasts to analyses. The first method is used to compare both a product's forecasts to its own analysis and to the other product's analysis. The latter two methods only consider a forecast compared to its own analysis.

3.3.1 Pixel To Pixel

Using a direct pixel-to-pixel approach, general field differences are examined through the mean error and root-mean-squared error. Mean error provides information on the overall relative tendencies (e.g., product A produces more intense fields than product B), while the root-mean-squared error provides information about the typical magnitude of the difference in field values.

3.3.2 Fractions Skill Score (FSS)

The Fractions Skill Score (FSS), described by Roberts and Lean (2008), supports the evaluation of the resolution of information in a product by comparing the fractional coverage of a forecast with an observation for a given neighborhood about a pixel, for all pixels in the field. This comparison is performed for various neighborhood sizes to assess product behavior at various resolutions. FSS ranges from 0.0 to 1.0, with 0.0 indicating a complete mismatch of fields, and a value of 1.0 indicating complete agreement in the number of forecasted pixels and number of observed pixels. Figure 3.1 provides a graphical depiction of FSS, along with the mathematical formula.



$$\mathrm{FSS} = 1 - \frac{\frac{1}{N}\sum_{i=1}^{N}(P_{fcst} - P_{obs})^2}{\frac{1}{N}\sum_{i=1}^{N}P_{fcst}^{\ 2} + \frac{1}{N}\sum_{i=1}^{N}P_{obs}^{\ 2}}$$

Australian Government
Bureau of Meteorology

FIGURE 3.1: VISUAL REPRESENTATION AND EQUATION FOR FRATIONS SKILL SCORE (FSS) TAKEN FROM EBERT, 2ND QPF CONFERENCE, BOULDER, CO, 5-8 JUNE 2006

As the area used to compute the fractions increases, the score will asymptote to a value that depends on the ratio between the forecast and observed frequencies of the event; the closer the asymptotic value is to 1.0, the smaller the forecast bias.

3.3.3 Flow Constraint Index (FCI)

The Flow constraint Index (FCI; Layne and Lack 2010) is used to convert convective weather products into a measure of airspace constraint. This technique provides an en-route, strategic planning context in which to assess convective weather products. The FCI is a specific implementation of the Mincut Max-Flow approach, and involves choosing a geometry to partition the airspace into a set of corridors of traffic flow. Example geometries include super-high-altitude sectors, airway-based geometries, as well as regular hexagonal geometries approximating the average size of a sector or ARTCC. The individual corridor FCI values are aggregated across the domain through the use of a corridor weighting scheme. Examples include weighting all corridors equally, or weighting each corridor by its corresponding traffic density.

For this assessment, the geometry is defined by the standard high-altitude jet routes. Each airway is buffered on either side by 20 nmi and partitioned into 80-nmi long segments; the traffic-density-based weighting is determined per 40x80-nmi segment. Traffic density is derived from ASDI data, using traffic determined by major carrier operations at OEP 35 airports, and represents a climatology of the 'best case scenario', i.e., traffic in the absence of weather. This traffic weighting is stratified by day of week and hour of day. FCI is computed for each airway segment and has a range of 0.0–1.0, where a value of 1.0 corresponds to most constrained, 0.0 corresponds to no constraint.

Figure 3.2 provides a schematic of the FCI calculation.

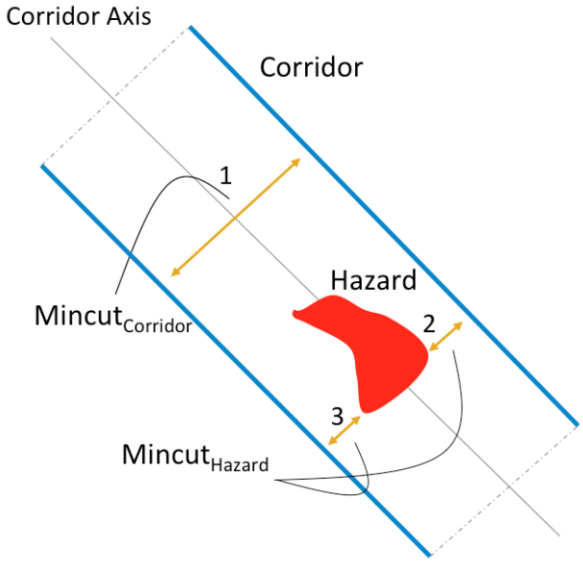


FIGURE 3.2: THE COMPUTATION OF FCI. BLUE LINES REPRESENT CORRIDOR BOUNDARIES; THE RED AREA IS THE AREA OF HAZARDOUS WEATHER. FLOW CONSTRAINT IS EQUAL TO 1- (MINCUT$_{HAZARD}$ /MINCUT$_{CORRIDOR}$), WHERE MINCUT$_{HAZARD}$ IS REPRESENTED BY ARROWS 2 AND 3, THE DISTANCE ACROSS THE AVAILABLE AIRSPACE AROUND A HAZARD, AND MINCUT$_{CORRIDOR}$ IS REPRESENTED BY ARROW 1, THE DISTANCE ACROSS THE CORRIDOR IN ABSENCE OF HAZARDS.

3.4 MRMS AND CIWS COMPARISON TO METAR OBSERVATIONS

METARs are included as an observation set for verification of VIL and ET. It is expected that when a METAR reports precipitation, specifically rainfall, that VIL and ET should be non-zero. In addition, when the METAR reports heavy rainfall (i.e., "+RA"), the frequency of non-zero VIL should be even greater. Conversely, when a METAR reports no precipitation, VIL should be zero most of the time, with an even greater frequency of zero VIL expected for METARs that report clear skies.

3.5 CASE STUDIES

Case Studies provide an in-depth look at the MRMS and CIWS fields during significant weather events. Events were selected based on impactful days to the National Airspace System (NAS). Alternative observation sets (radar, satellite, METAR, and sounding data) are incorporated to determine the plausibility of the MRMS and CIWS fields.

4 Evaluation Results

4.1 Field Characteristics

4.1.1 Climatological Maps

Figure 4.1 shows a climotological map using combined VIL and ET thresholds corresponding to significant convection considered impactful to air traffic, namely VIL ≥ 3.5 kg/m² and ET ≥ 20,000 ft, for April 2014. It can be seen that the frequency of occurrence and geographical extent of convection is notably greater in CIWS products than MRMS products, for both the forecasts and analyses. The patterns of magnitude and extent appear to be relatively consistent across analyses and forecasts for both CIWS and MRMS, although there are slight differences in the maximum frequency at a given pixel for CIWS.

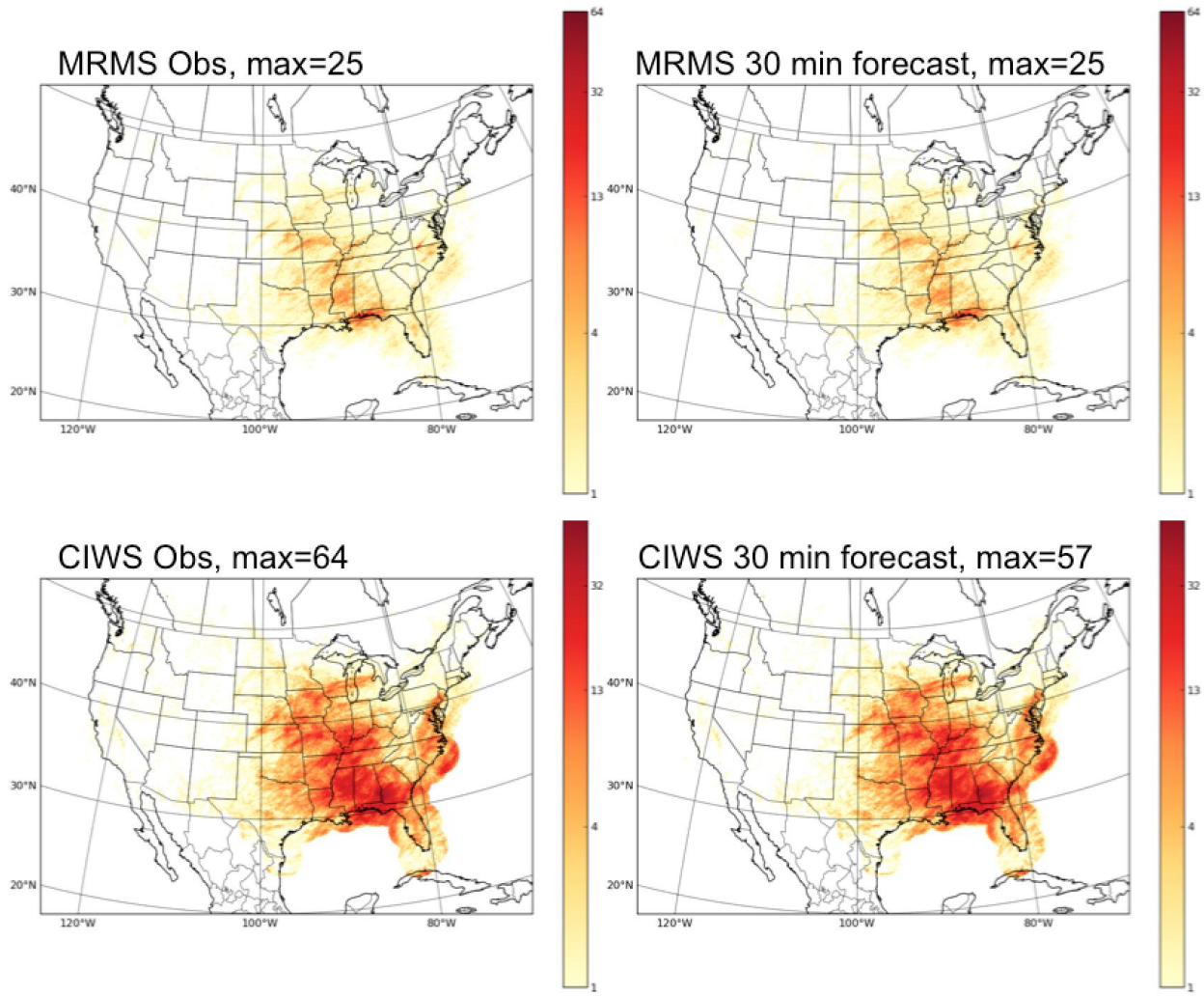


FIGURE 4.1: THE NUMBER OF OCCURANCES OF VIL ≥ 3.5 KG/M² AND ET > 20,000 FT OF ANALYSES (LEFT) AND 30-MINUTE FORECASTS (RIGHT) FROM MRMS (TOP) AND CIWS (BOTTOM) IN APRIL OF 2014. THE 'MAX' INDICATES THE MAXIMUM NUMBER OF OCCURANCES AT A GIVEN PIXEL. COLORBARS ARE EQUAL FOR ALL IMAGES.

4.1.2 Distributions

A distribution of all VIL values associated with ET > 0 ft, stratified by region, is presented in Figure 4.2. CIWS VIL is seen to have high values (up to 80 kg/m^2) in all geographic regions, while MRMS VIL values rarely exceed 70 kg/m^2 regardless of region. This behavior in the two products may be due to the differing approaches in the VIL algorithms (refer to data description in CIWS and MRMS Analyses/Forecasts). In addition, the CIWS distribution is curiously similar for all regions, while the MRMS distribution shows substantial differences among the regions with the Central and Northeast regions seeing higher VIL values than the West and Southeast regions. Note that the gaps in the higher values of the CIWS distributions are an artifact of the discretization that results from the data storage approach for CIWS. The effects of these algorithms will be further evaluated in case studies presented in Section 4.5.

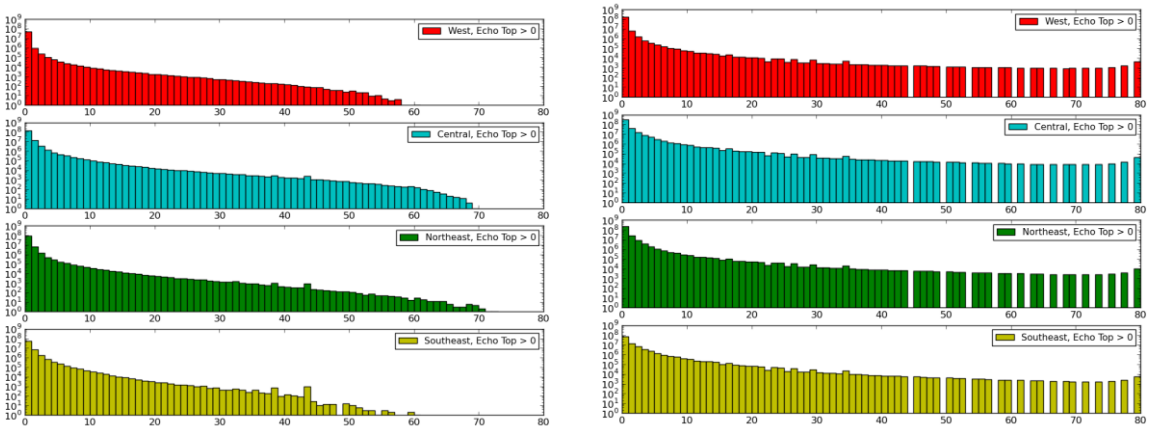


FIGURE 4.2: VIL, COUNTED INTO BINS OF 1 KG/M^2, FROM MRMS (LEFT) AND CIWS (RIGHT) ANALYSES WITH NON-ZERO ET FOR MAY OF 2014. COLORS INDICATE THE FOUR REGIONS OF INTEREST (WEST-RED, CENTRAL-AQUA, NORTHEAST-GREEN, SOUTHEAST-YELLOW).

Distributions of ET height are also examined, as presented in Figure 4.3. Differences can be seen in the MRMS and CIWS ET height, most notably for ET values greater than 50,000 ft, where the frequency of occurrence is substantially greater in MRMS analyses than in CIWS, when combined with VIL values above thresholds corresponding to hazardous weather (3.5 kg/m^2, 6.9 kg/m^2). This behavior occurs in all regions, though the very high ET values are most prevalent in the Central region and least prevalent in the West. Such a high frequency of ET values above 50,000 ft is not necessarily reflective of true atmospheric conditions.

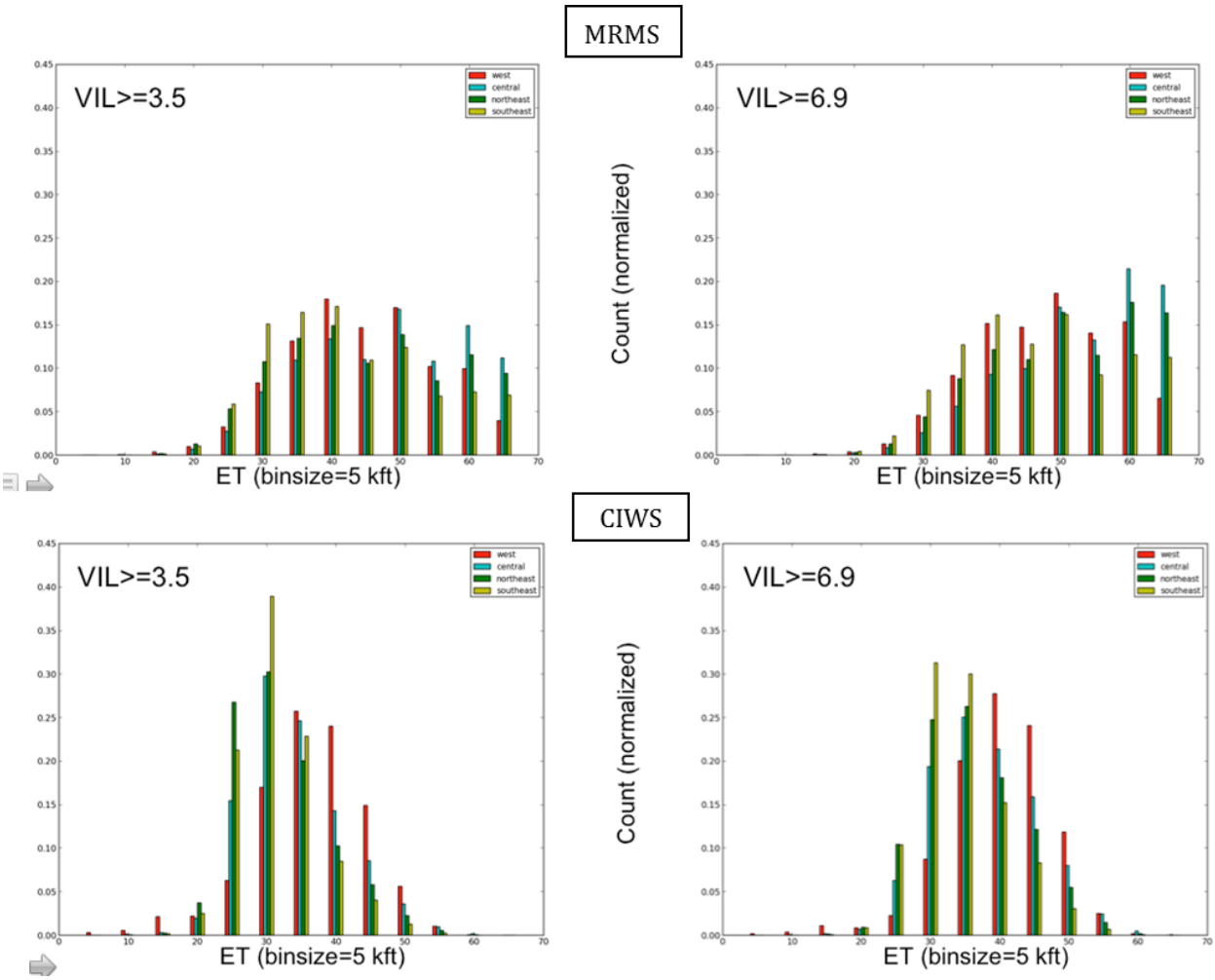


FIGURE 4.3: ECHO TOP HEIGHT, COUNTED INTO 5000 FT BINS, FOR MRMS (TOP) AND CIWS (BOTTOM) ANALYSES FOR VIL ≥ 3.5KG/M2 (LEFT) AND VIL ≥ 6.9KG/M² (RIGHT), FOR MAY OF 2014. COLORS INDICATE THE FOUR REGIONS OF INTEREST (WEST-RED, CENTRAL-AQUA, NORTHEAST-GREEN, SOUTHEAST-YELLOW).

4.1.3 EXAMPLE

Figure 4.4 is a snapshot of the MRMS and CIWS fields from 16 March 2014 that demonstrates findings from the evaluation of VIL and ET field characteristics. In the VIL field, a greater extent of significant VIL can be seen in CIWS (≥ 3.5 kg/m²) in Georgia and Tennessee, as compared to MRMS. The total extent of VIL > 0 kg/m² is greater in CIWS than MRMS, as seen in South Carolina and along the Georgia/Florida border. The ET fields also differ, with a number of instances in which MRMS ET is significantly higher than CIWS, most notably in Southern Alabama/Florida Panhandle, coastal South Carolina, and the northern Gulf of Mexico. The high ETs in the latter two regions correspond to low VIL values.

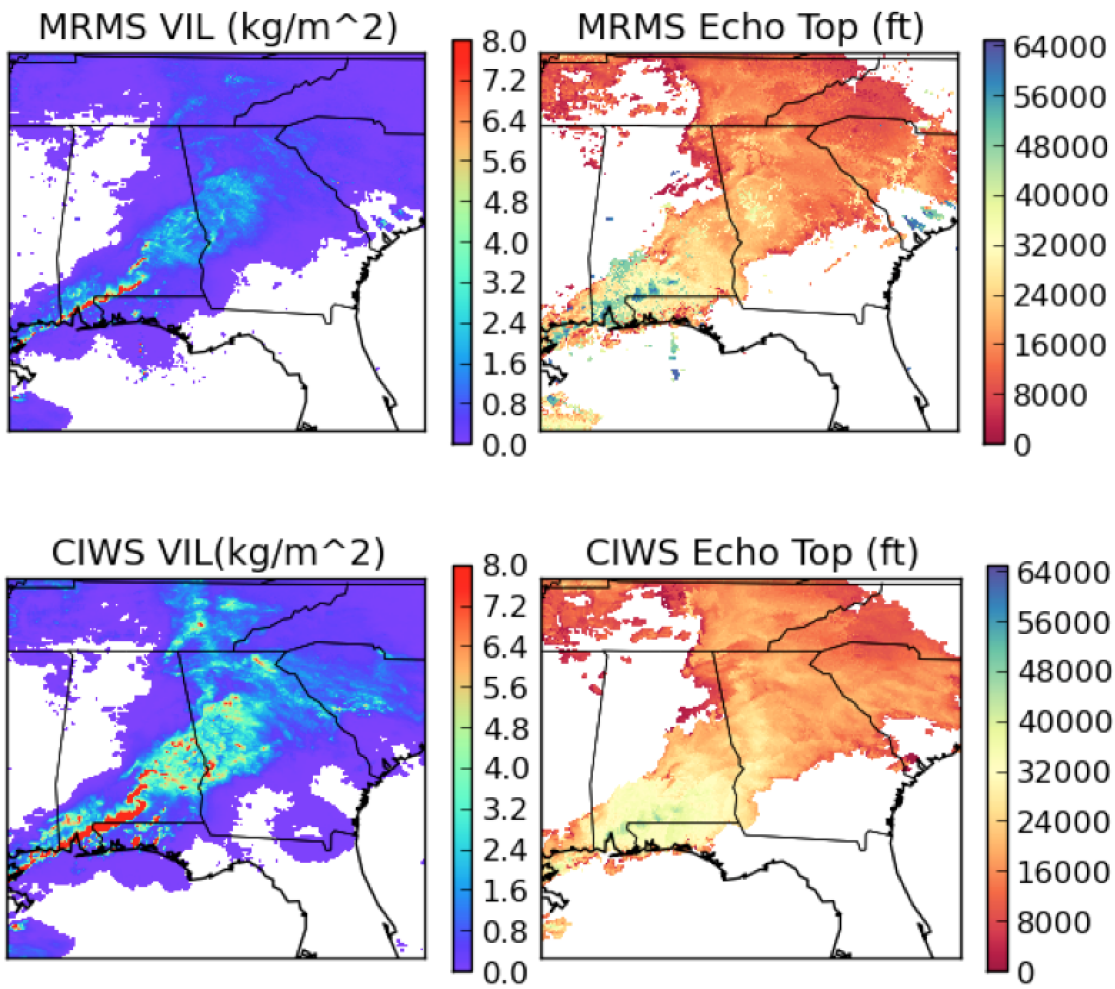


FIGURE 4.4: VIL (LEFT) AND ECHO TOP (RIGHT) FOR MRMS (TOP) AND CIWS (BOTTOM) VALID AT 0000 UTC ON 16 MARCH 2014. VIL VALUES ARE IN KG/M², AND ET IN FT.

4.1.4 Incorporation of Dual-Pol into MRMS: May 2013 Compared to May 2014

CIWS and MRMS data from May 2013 is compared to better understand the results of the incorporation of the new Dual-Polarization features of the NEXRAD radars into MRMS in May 2014. CIWS uses only the single-polarization variables, and so year-to-year changes should reflect meteorological differences alone, while MRMS year-to-year changes may be a combination of meteorological differences and the Dual-Pol upgrade. Meteorological fields indicate May 2013 had widespread intense convection across the central plains, while May 2014 had increased convection in the Southeast and along the Gulf Coast (not shown). Climatological aggregations similar to Figure 4.1 were computed for CIWS and MRMS for May 2013 and 2014. Figure 4.5 is a ratio of the May 2013 to 2014 climatologies used to evaluate year-to-year changes in the products. The regional shift in convection is readily identified in the CIWS difference map (Figure 4.5, right) with reductions (red) and increases (blue) in 2014 relative to 2013 that are similar in magnitude. The MRMS difference map (Figure 4.5, left) shows 2014 to have widespread decreases, particularly

through the Central and Southern Plains, without a corresponding increase. The reduced frequency in the occurrence of higher VIL values in 2014 is even more evident when comparing the distribution of VIL values from the two seasons (Figure 4.6; note the log scale of the distributions). Beginning around 5 kg/m^2, the distribution of VIL intensity in 2014 falls off quickly, becoming a full order of magnitude less common than in 2013. For CIWS, there is a smaller decline in the occurrence of higher VIL values, starting around 15 kg/m^2. Furthermore, the sum of all pixels with ET > 0, corresponding to the presence of convection, shows the total count for MRMS in 2014 had 46% of the total count of 2013, with CIWS 2014 data having 66% as many pixels as 2013.

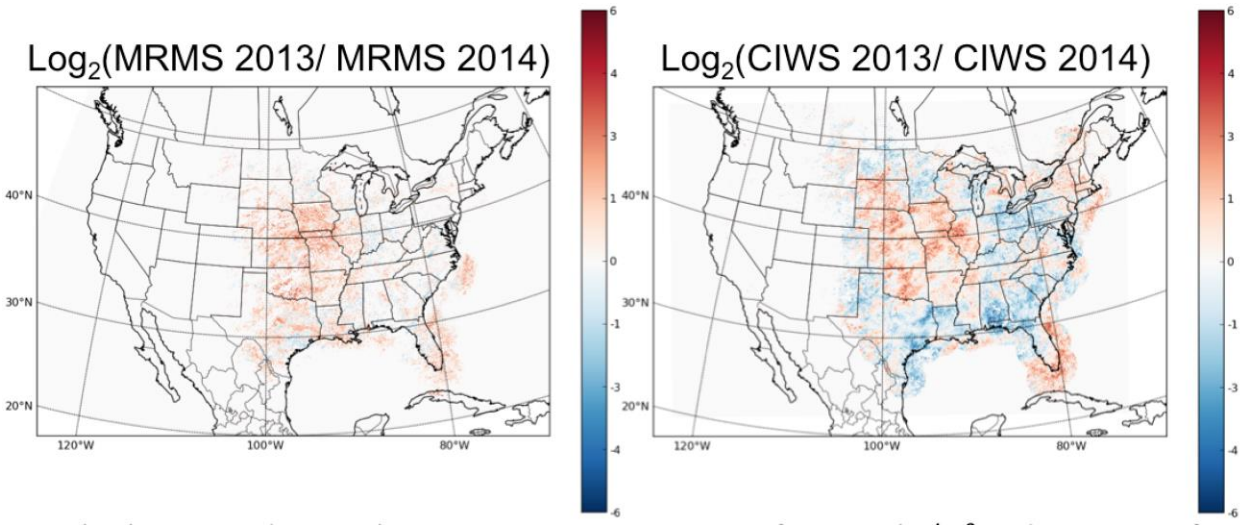


FIGURE 4.5: NUMBER OF OCCURANCES OF VIL ≥ 3.5 KG/M^2 AND ET > 20,000 FT EXPRESSED AS A LOG BASE 2 RATIO OF 2013 TO 2014 FOR MRMS (LEFT) AND CIWS (RIGHT). RED INDICATE PIXELS WHERE 2013 OCCURANCES EXCEED 2014, AND BLUE INDICATES WHERE 2014 OCCURANCES EXCEED 2013.

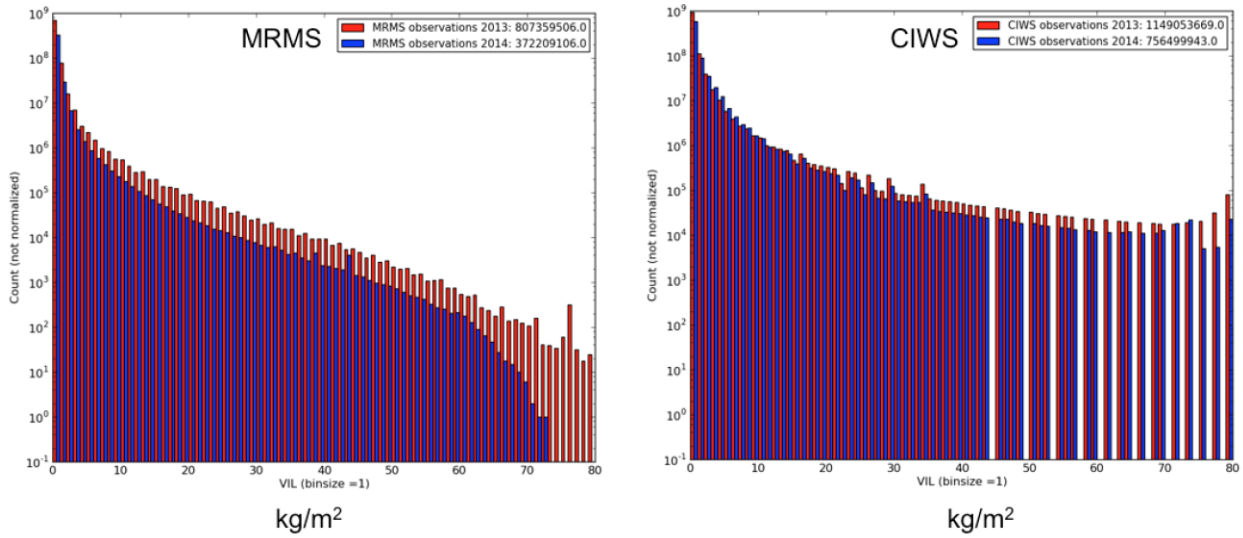


FIGURE 4.6: VIL, COUNTED INTO 1 KG/M² BINS FOR MRMS (LEFT) AND CIWS (RIGHT) ANALYSES WITH NON-ZERO ET, FOR MAY OF 2013 (RED) AND MAY 2014 (BLUE).

Figure 4.7 stratifies the VIL distribution by region, expressed as a ratio of 2013 to 2014. MRMS has notable reductions in most VIL bins in the Southeast, Central, and West regions in 2014; the one exception is the Northeast, in which there is more VIL > 30 kg/m² in 2014. CIWS shows slight reductions in the Southeast, Northeast, and West regions, and an increase in the Central region, similar in nature to geographical distributions shown in Figure 4.5 These findings are consistent in suggesting Dual-Pol plays a role in the year-to-year differences in MRMS.

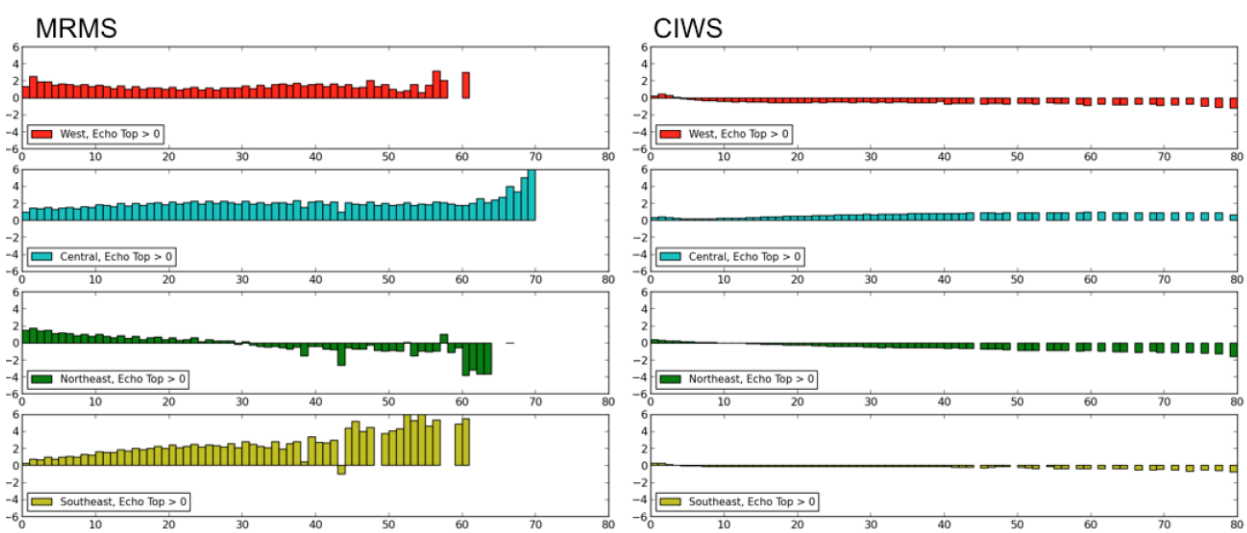


FIGURE 4.7: VIL, COUNTED INTO 1 KG/M2 BINS FOR MRMS (LEFT) AND CIWS (RIGHT) ANALYSES WITH NON-ZERO ET EXPRESSED AS A LOG BASE 2 RATIO OF 2013 TO 2014. COLORS INDICATE THE FOUR REGIONS OF INTEREST (WEST-RED, CENTRAL-AQUA, NORTHEAST-GREEN, SOUTHEAST-YELLOW).

4.1.5 Additional Anomalies

Additional anomalies that were identified are listed below.

1. MRMS does not utilize the value of 0 in its VIL field. Instead, fill values are used where 0 would be expected. As a result, it cannot be determined whether a fill value signifies a definite no-VIL area, or an area in which there is no data.
2. CIWS data has large areal extent of low VIL values in analyses that are not present in the forecast product. An example is shown in Figure 4.8. These low VIL values are not necessarily representative of true atmospheric conditions and could be problematic for automated systems.

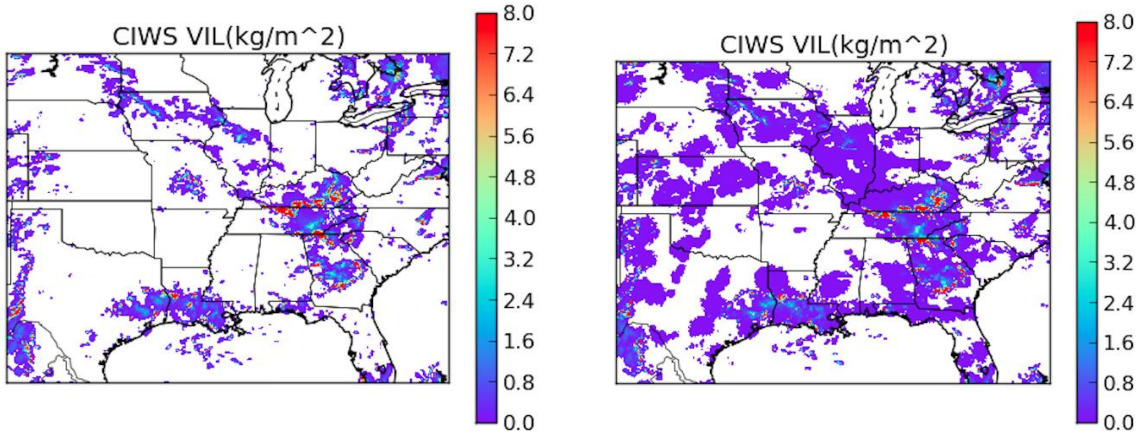


FIGURE 4.8: CIWS 30-MINUTE VIL FORECAST, VALID 2230 UTC ON 20 AUGUST, (LEFT) AND CIWS ANALYSIS VALID AT THE SAME TIME (RIGHT).

3. A 30-kg/m^2 value cap was found in the MRMS forecast product (Figure 4.9, left). NSSL was notified in July 2014, and this has since been corrected.
4. An unusual VIL signature was noted along the North Carolina/Virginia border (Figure 4.9, right), likely to be a quality control problem. NSSL was notified of this during the preliminary assessment results.

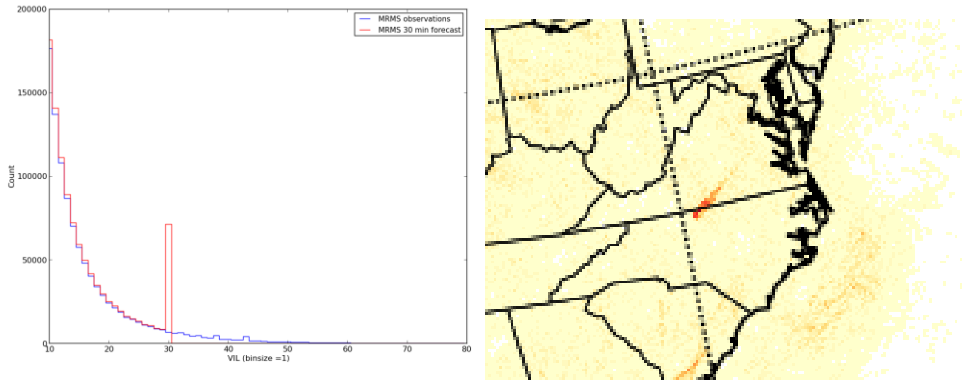


FIGURE 4.9: MRMS FORECAST CAP AT 30 KG/M^2 (LEFT) AND FREQUENT OCCURRANCE OF VIL ≥ 3.5 KG/M^2 ALONG NORTH CAROLINA/VIRGINIA BORDER IN MRMS DATA (RIGHT).

4.2 FORECAST ASSESSMENT

MRMS and CIWS forecasts are compared to MRMS and CIWS analyses using three methods: a direct pixel-to-pixel comparison yielding mean error (giving the bias of the forecasts relative to the analysis) and mean squared error (giving the typical magnitude of the intensity difference between forecast and analysis), Fractions Skill Score (FSS), and Flow Constraint Index (FCI). Unless otherwise noted, MRMS and CIWS forecasts are compared to their respective analyses.

4.2.1 Pixel to Pixel

When comparing a forecast of VIL or ET to the product's own analysis at its valid time, the differences between the CIWS forecasts and analyses are of greater magnitude than that seen between the MRMS forecasts and analyses (Figure 4.10, left). CIWS differences are negative for VIL (> 0 kg/m^2) and ET (> 0 ft), implying that the forecast values are less than analyses values in areas of overlap. This is consistent with earlier findings that show CIWS analyses have large areas of relatively small values of VIL (cf., Figure 4.8). The RMS difference (Figure 4.10, right) is higher for VIL in CIWS than for MRMS, with RMSE for ET about the same for both products. So, while the CIWS forecast fields have a low bias relative to the analysis, the typical magnitude of the forecast-analysis difference is similar to that seen in MRMS for ET and notably larger than that seen in MRMS for VIL.

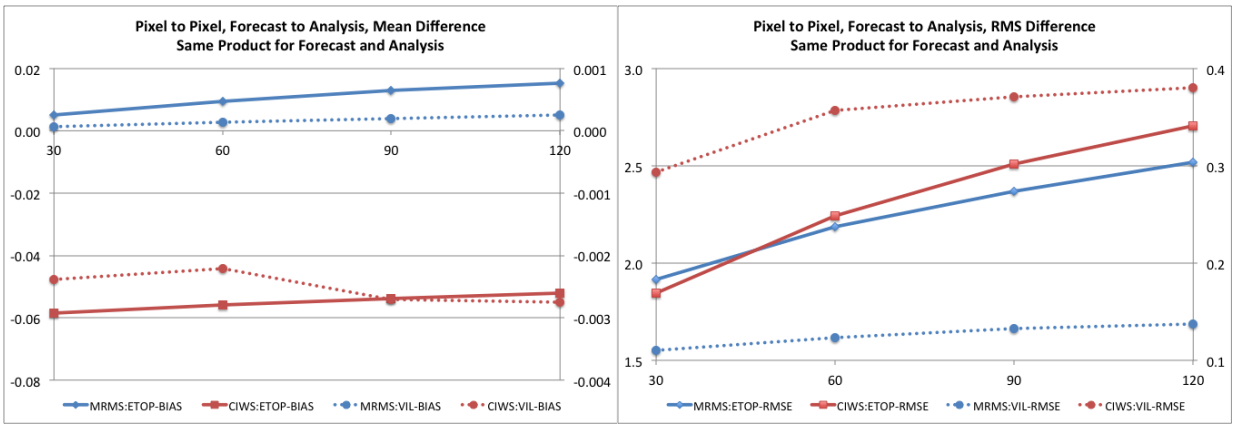


FIGURE 4.10: MEAN DIFFERENCE (LEFT) AND ROOT MEAN SQUARED DIFFERENCE (RIGHT) OF ECHO TOP HEIGHT (SOLID; LEFT AXIS) AND VERTICALLY INTEGRATED LIQUID (DOTTED; RIGHT AXIS) FOR MRMS FORECASTS COMPARED TO MRMS ANALYSES VALID AT THE SAME TIME (BLUE) AND FOR CIWS FORECASTS COMPARED TO CIWS ANALYSES VALID AT THE SAME TIME (RED). RESULTS ARE FOR THE PERIOD OF DECEMBER 2013 THROUGH MAY OF 2014.

When comparing a forecast to the opposite product's analysis at its valid time, the mean differences (Figure 4.11, left) between forecast and analysis VIL and ET fields for MRMS forecast to CIWS analyses are greater in absolute magnitude than CIWS to MRMS, and negative (negative implying that the forecast area is smaller than the analysis). Differences between CIWS forecasts and MRMS analyses, on the other hand, are lesser in absolute magnitude, and positive (implying the forecast area is larger than the analysis). The RMS differences (Figure 4.11, right), for VIL, are greater for MRMS forecasts than for CIWS forecasts compared to the opposite analysis. For ET, it is the CIWS forecasts that have a greater RMS difference when compared to the opposite analysis, though RMS differences are nearly identical for the two products by the 120 minute lead. As with the mean difference, the RMS differences when comparing a forecast product to the opposite analysis are of a significantly larger magnitude than when comparing that forecast product to its own analysis.

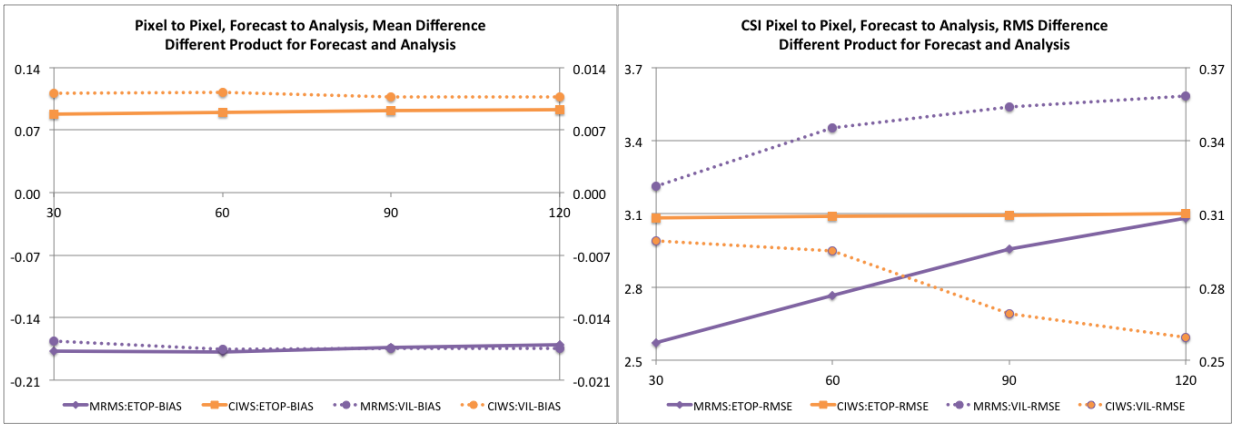


FIGURE 4.11: MEAN DIFFERENCE (LEFT) AND MEAN SQUARED DIFFERENCE (RIGHT) OF ECHO TOP HEIGHT (SOLID) AND VERTICALLY INTEGRATED LIQUID (DOTTED) FOR MRMS FORECASTS COMPARED TO CIWS ANALYSES VALID AT THE SAME TIME (PURPLE) AND FOR CIWS FORECASTS COMPARED TO MRMS ANALYSES VALID AT THE SAME TIME (ORANGE). RESULTS ARE FOR THE PERIOD OF DECEMBER 2013 THROUGH MAY OF 2014.

4.2.2 Fractions Skill Score (FSS)

The FSS gives insights into the scale of information available from a forecast. As the size of the neighborhood increases, the FSS should increase from the magnitude of the grid-scale error, asymptoting to a level corresponding to the bias of the forecast (and therefore, to a value of one for an unbiased forecast).

In general, for a given neighborhood and lead time, the FSS for CIWS is closer to 1 than the FSS for MRMS (Figure 4.12), an exception being that the 30-minute lead forecasts from MRMS outperform CIWS at the 3 and 15 km scale when using a VIL threshold of 0.76 kg/m^2. In general, MRMS has a consistent decrease in performance for longer leads, whereas the CIWS 60-minute lead is nearly indistinguishable from the CIWS 30-minute lead.

When considering a VIL threshold of 3.5 kg/m^2 (Figure 4.12, bottom) versus 0.76 kg/m^2 (Figure 4.12, top), the skill of both products is reduced—the smaller scale of the 3.5-kg/m^2 features makes them more difficult to forecast—but patterns are similar. In general, a larger scale is necessary for the 3.5-kg/m^2 threshold to get performance similar to that of the 0.76-kg/m^2 threshold.

Note that for the 3.5 kg/m^2 threshold, the MRMS FSS scores are lower and more flat for increased neighborhood sizes as compared to CIWS. This indicates that MRMS has less spatial information for this VIL threshold, but it obtains that level of information at a finer spatial scale.

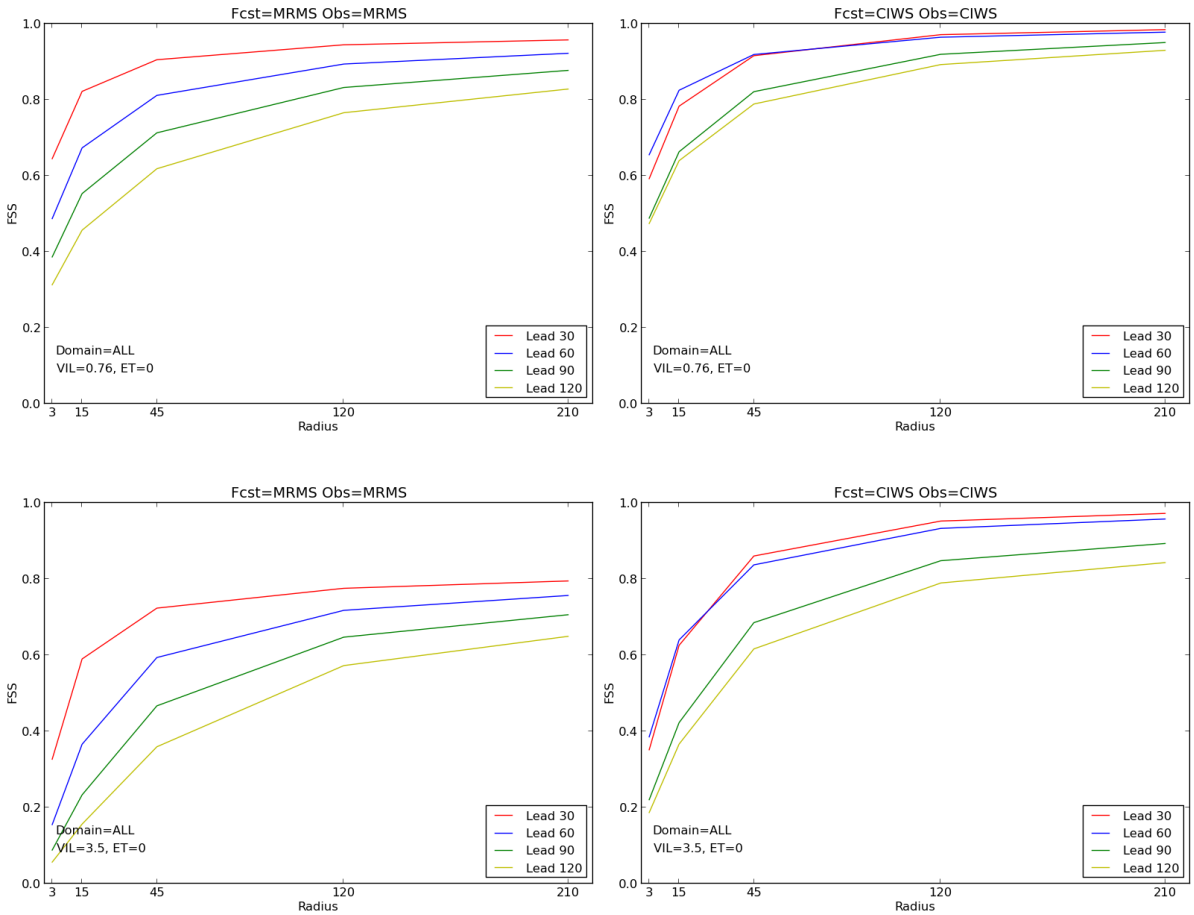


FIGURE 4.12: FSS AS A FUNCTION OF RADIUS USING A VIL THRESHOLD OF 0.76 KG/M² (TOP) AND 3.5 KG/M² (BOTTOM) AT ALL NON-ZERO ECHO TOPS, FOR MRMS FORECASTS COMPARED TO MRMS ANALYSES VALID AT THE SAME TIME (LEFT) AND FOR CIWS FORECASTS COMPARED TO CIWS ANALYSES VALID AT THE SAME TIME (RIGHT), FOR THE PERIOD DECEMBER 2013 – MAY 2014.

4.2.3 Flow Constraint Index (FCI)

FCI provides an en-route context in which to evaluate convective weather products by considering storm structure and orientation in addition to location. For forecasts of a 30-minute lead-time, MRMS and CIWS measures of agreement are similar at all FCI thresholds for VIL ≥ 0.76 kg/m² (Figure 4.13, top), and at low FCI thresholds for VIL ≥ 3.5 kg/m² (Figure 4.13, bottom). For the other combinations of VIL threshold and lead, CIWS forecasts are more skillful than MRMS forecasts, relative to its own analysis (Figure 4.13). When lead-time is increased, the measure of agreement between the analyses and forecasts for MRMS falls off more substantially than that for CIWS. While MRMS agreement falls off steadily with lead-time, the decline for CIWS is nonlinear, with little change between the 30- and 60-minute or 90 and 120-minute leads, but a marked drop between 60 and 90 minutes. Similar results were seen when examining additional VIL/ET threshold combinations and examining the geographic sub-regions.

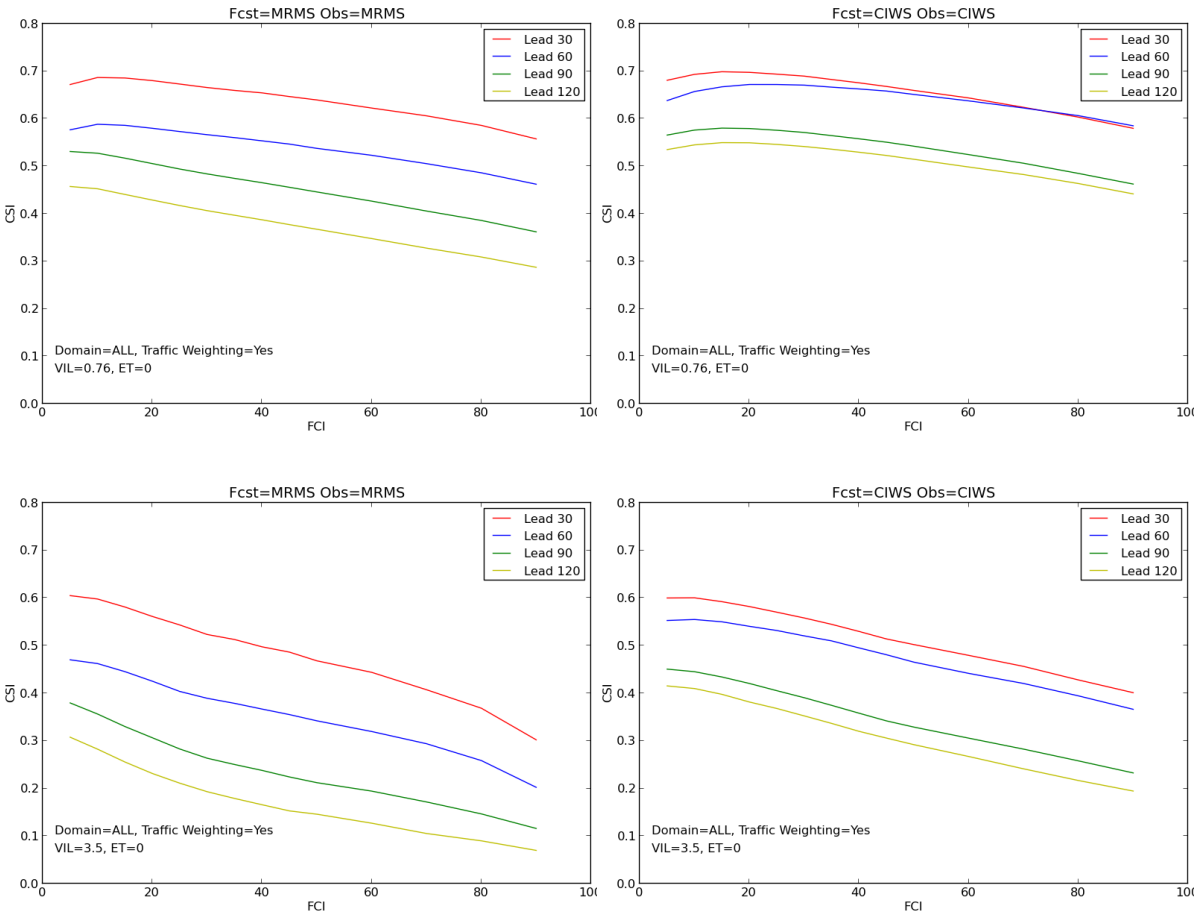


FIGURE 4.13: CSI AS A FUNCTION OF FCI THRESHOLD USING A VIL THRESHOLD OF 0.76 KG/M² (TOP) AND 3.5 KG/M² (BOTTOM) AT ALL NON-ZERO ECHO TOPS, FOR MRMS FORECASTS COMPARED TO MRMS ANALYSES VALID AT THE SAME TIME (LEFT) AND FOR CIWS FORECASTS COMPARED TO CIWS ANALYSES VALID AT THE SAME TIME (RIGHT), FOR THE PERIOD DECEMBER 2013 – MAY 2014.

4.3 COMPARISON TO METAR OBSERVATIONS

When a METAR reports rain, CIWS analyses and forecasts have a greater percentage of pixels with VIL > 0 kg/m² (Figure 4.14, left) and VIL ≥ 0.14 kg/m² (Figure 4.14, right) compared to MRMS. As expected, both products have a higher hit rate for moderate-or-greater rainfall (RA or +RA, shown in the dotted lines). Expansion to a larger neighborhood of pixels around a METAR site (not shown) does not change the results significantly, though the difference in product performance decreases. The lesser coverage of MRMS increases the likelihood of having no VIL where rain is recorded, but often MRMS does indicate VIL not too far from the METAR site.

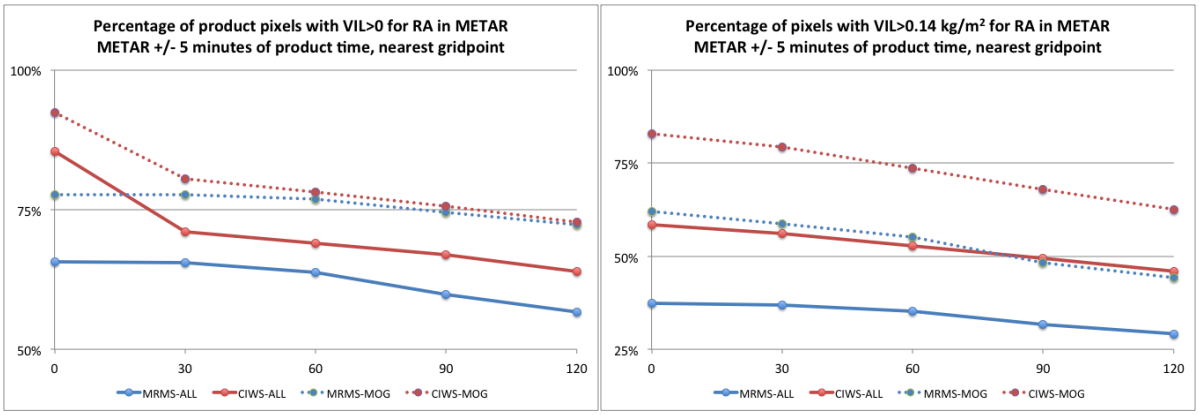


FIGURE 4.14: PERCENTAGE OF MRMS (BLUE) AND CIWS (RED) PIXELS CONTAINING VIL > 0 KG/M² (LEFT) AND VIL>0.14 KG/M² (RIGHT) WHEN A METAR REPORTS AND RAIN (SOLID) AND WHEN A METAR REPORTS MODERATE OR GREATER RAIN (DOTTED) PLOTTED AS A FUNCTION OF LEAD TIME (0 IS THE ANALYSIS).

When a METAR reports no rain, CIWS analyses have a greater percentage of pixels containing VIL > 0 kg/m² (Figure 4.15, left) and a greater percentage of pixels with VIL ≥ 0.14 kg/m² (Figure 4.15, right) as compared to MRMS, though non-rain does not necessarily mean non-VIL. When considering only the METARS that report clear skies (conditions in which only small VIL, if any, is expected), CIWS forecasts have a smaller percentage of VIL ≥ 0.14 kg/m², but the opposite is true for the analyses. MRMS VIL analyses are more consistent with METAR reports of clear skies than CIWS analyses.

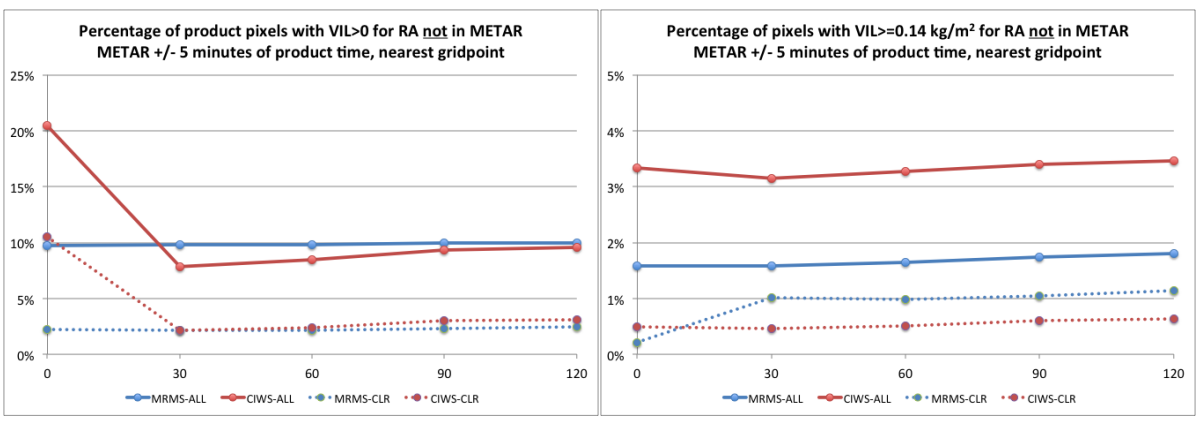


FIGURE 4.15: PERCENTAGE OF MRMS (BLUE) AND CIWS (RED) PIXELS CONTAINING VIL > 0 KG/M² (LEFT) AND VIL > 0.14 KG/M² (RIGHT) WHEN A METAR DOES NOT REPORT RAIN (SOLID) AND WHEN A METAR REPORTS CLEAR SKY (DOTTED) PLOTTED AS A FUNCTION OF LEAD TIME (0 IS THE ANALYSIS).

4.4 INTRA-MODEL CONSISTENCY

Using the dichotomous measure CSI, for VIL ≥ 0.76 or 3.5 kg/m² with ET > 0, CIWS forecasts are more consistent with their analyses than is the case for MRMS forecasts compared to their analyses (Figure 4.16, left). The CSI is higher for a lower VIL threshold (0.76 vs. 3.5 kg/m²). When a product is compared to the prior forecast verifying at the same time (Figure 4.16, right) the CSI is also

higher for CIWS than MRMS. In other words, CIWS forecasts are more similar to subsequent CIWS forecasts valid at the same time as well as the corresponding CIWS analysis than is the case for MRMS forecasts.

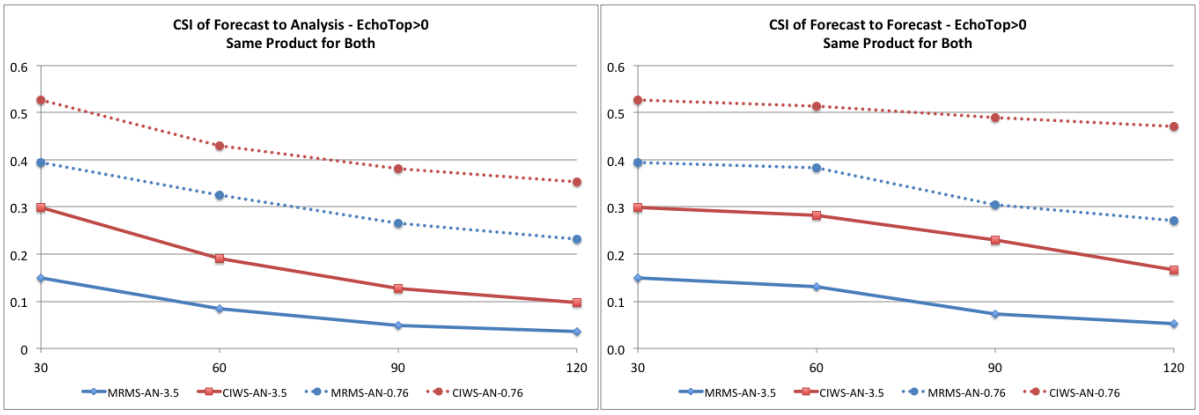


FIGURE 4.16: CSI OF FORECASTS TO ANALYSES (LEFT) AND FORECASTS TO PRIOR FORECAST VERIFYING AT THE SAME TIME (RIGHT) FOR MRMS (BLUE) AND CIWS (RED), FOR VIL ≥ 3.5KG/M² (SOLID) AND VIL ≥ 0.76KG/M² (DOTTED), FOR THE PERIOD DECEMBER 2013 – MAY 2014.

4.5 CASE STUDIES

In addition to the aggregate statistics examined so far, it is instructive to investigate individual cases to see how the statistical trends manifest themselves physically. Two cases are presented herein.

4.5.1 8-9 MAY 2014

From the afternoon of 8 May 2014 into the early morning of 9 May 2014, there were multiple rounds of convection across central and eastern Texas. This convection resulted in 69% delayed gate arrivals at DFW, compared to an average of 15% in May 2014. A broad look at the fields from the two products at 1200 UTC on 8 May 2014 (Figure 4.17) shows a short convective line in N TX with weaker convection extended into S OK. In MRMS, the storm is weaker but has the same structure and location. In contrast, three hours later (Figure 4.18) the image suffers from obvious outages in MRMS data, resulting in the convection in N TX and S OK being nearly absent in this image. The outages are mainly confined to the 1500 – 2100 UTC timeframe. Outages were not found upon inspection of the corresponding loop on the MRMS website, indicating this issue is likely due to the FAA data feed.

The VIL values in CIWS are larger than those in MRMS, consistent with results presented thus far. MRMS seems to produce erroneous high ET in non-storm areas (e.g., streaks across E TX and the Central Plains, contiguous area in central KS) and within the storms (e.g., the short line in south-central OK). Also, CIWS near-zero VIL covers a large portion of the domain at 1200 UTC, and even more so in the early morning hours (not shown).

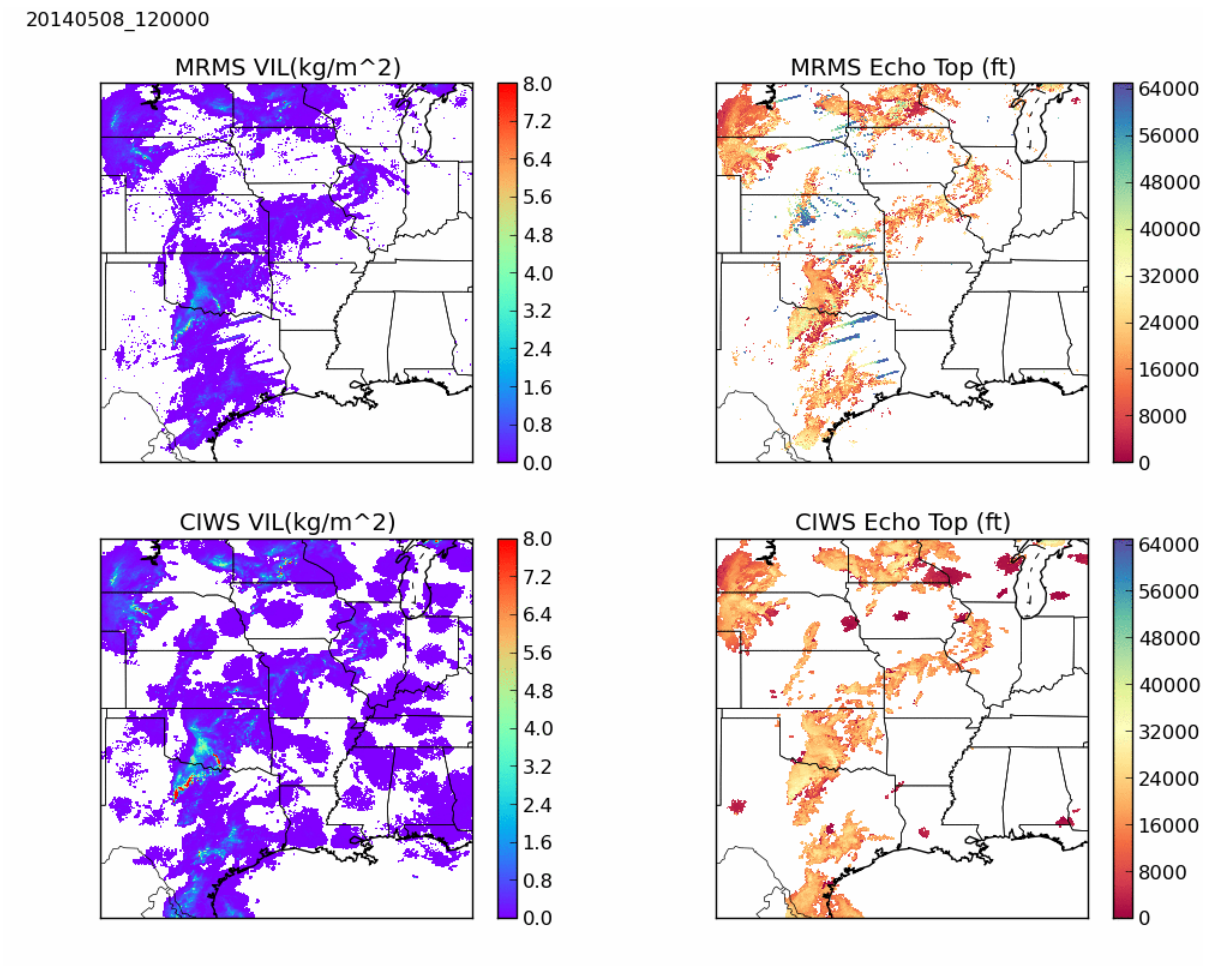


FIGURE 4.17: VIL (LEFT) AND ET (RIGHT) FROM MRMS (TOP) AND CIWS (BOTTOM) VALID AT 1200 UTC ON 8 MAY 2014.

Figure 4.18 displays the VIL and ET fields three hours later (1500 UTC on 8 May 2014). The visible satellite imagery and METAR reports valid at the same time (Figure 4.19) show the cloudiness along the Texas Gulf Coast with embedded rain and thunderstorm reports (TS/RA and TS/RA+). MRMS shows significantly less VIL in these areas when compared to CIWS.

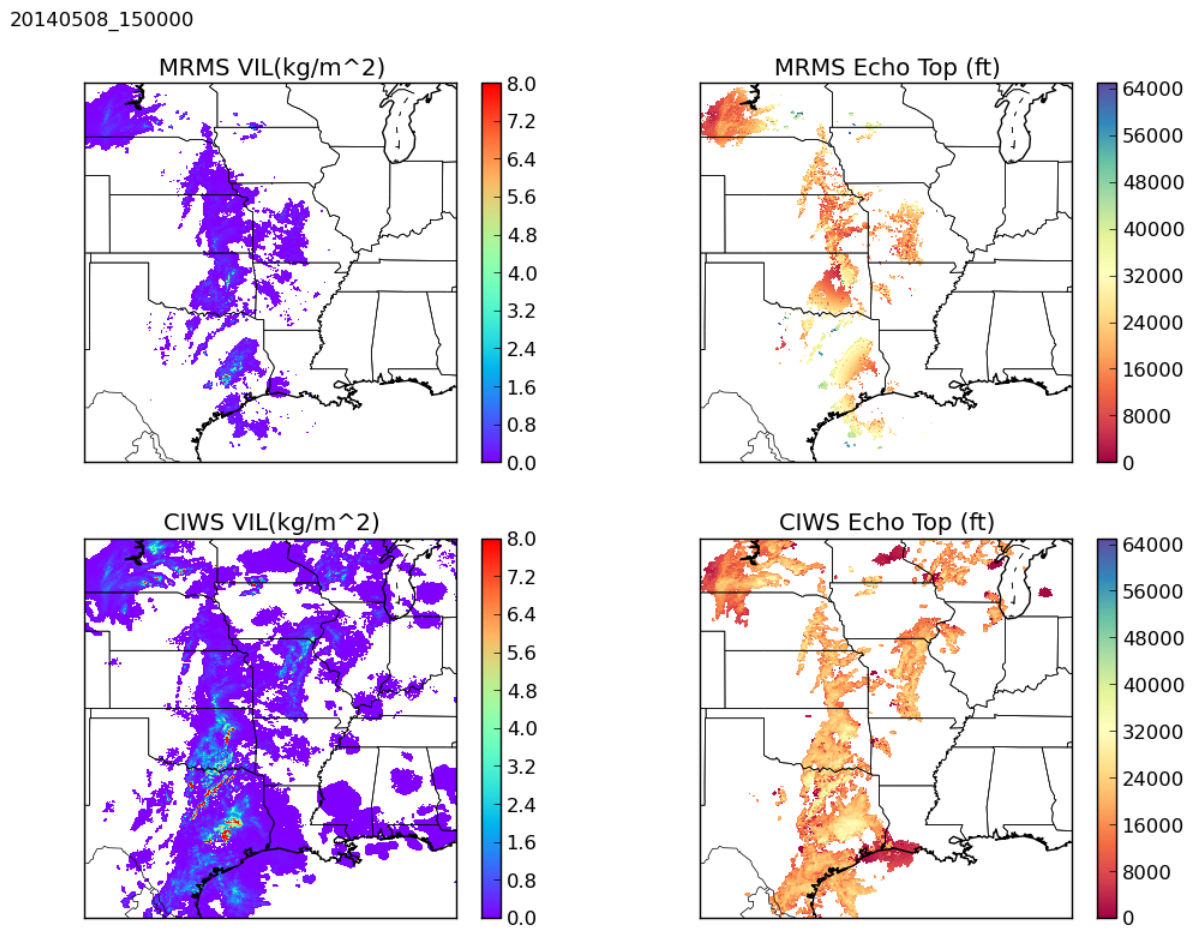


FIGURE 4.18: VIL (LEFT) AND ET (RIGHT) FROM MRMS (TOP) AND CIWS (BOTTOM) VALID AT 1200 UTC ON 8 MAY 2014.

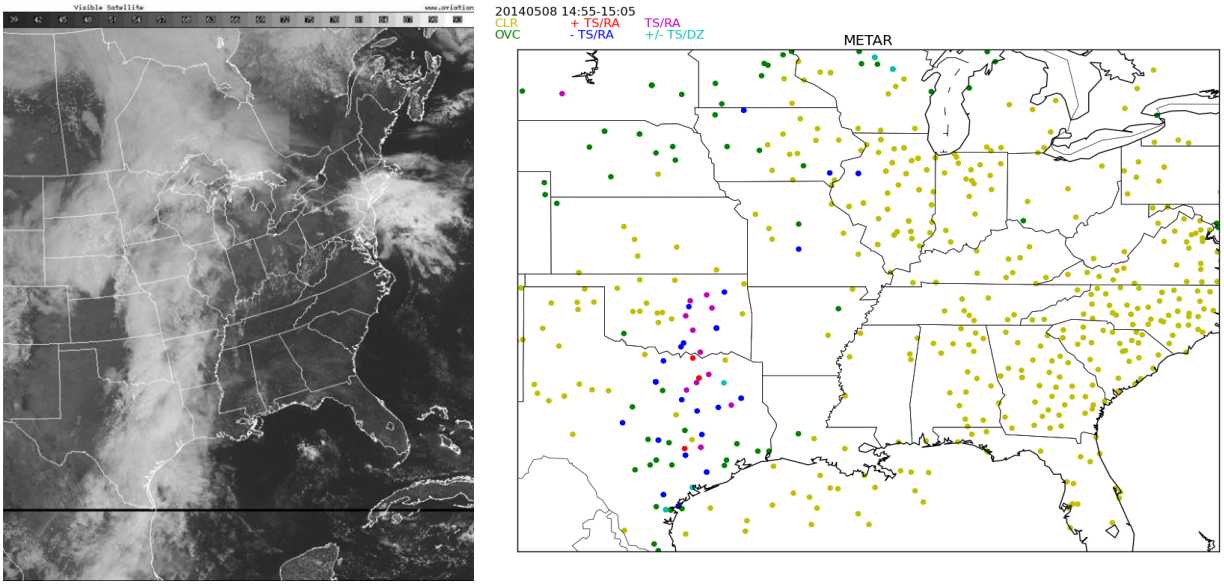


FIGURE 4.19: VISIBLE SATELLITE IMAGERY (LEFT) AND METAR REPORTS (RIGHT) VALID AT 1500 UTC ON 8 MAY 2014.

Analyzing infrared satellite imagery in conjunction with sounding plots gives an estimate of cloud top, which can in turn help evaluate echo top fields. In the infrared satellite image valid at 0230 UTC on 9 May 2014 (Figure 4.20, left), the cloud top temperatures are approximately -55 °C in the vicinity of Dallas, Texas. The DFW sounding at 0000 UTC on 9 May 2014 (Figure 4.20, right) indicates that a temperature of -55 °C corresponds to an altitude of approximately 45,000 ft. Figure 4.21 shows the MRMS ET analysis at 0300 UTC has tops over 60,000 ft, whereas CIWS ET analysis has the ET closer to 35,000 ft. Given that the ET height is below cloud top height, the CIWS ET analysis appears to be more plausible in this case, than the MRMS ET analysis.

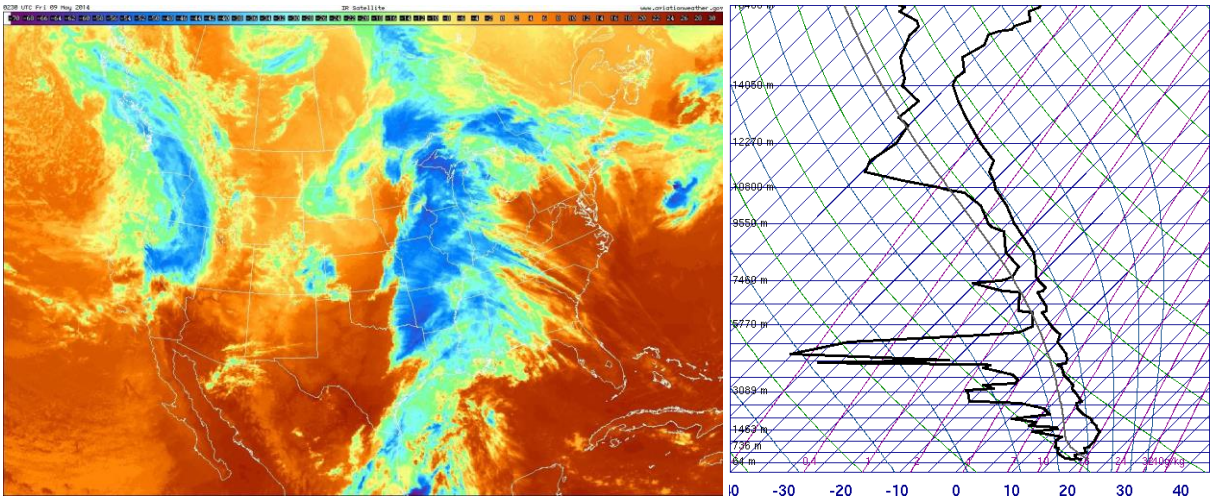


FIGURE 4.20: INFRARED SATELLITE IMAGERY VALID AT 0230 UTC ON 9 MAY 2014 (LEFT) AND DFW SOUNDING PLOT (RIGHT) VALID AT 0000 UTC ON 9 MAY 2014.

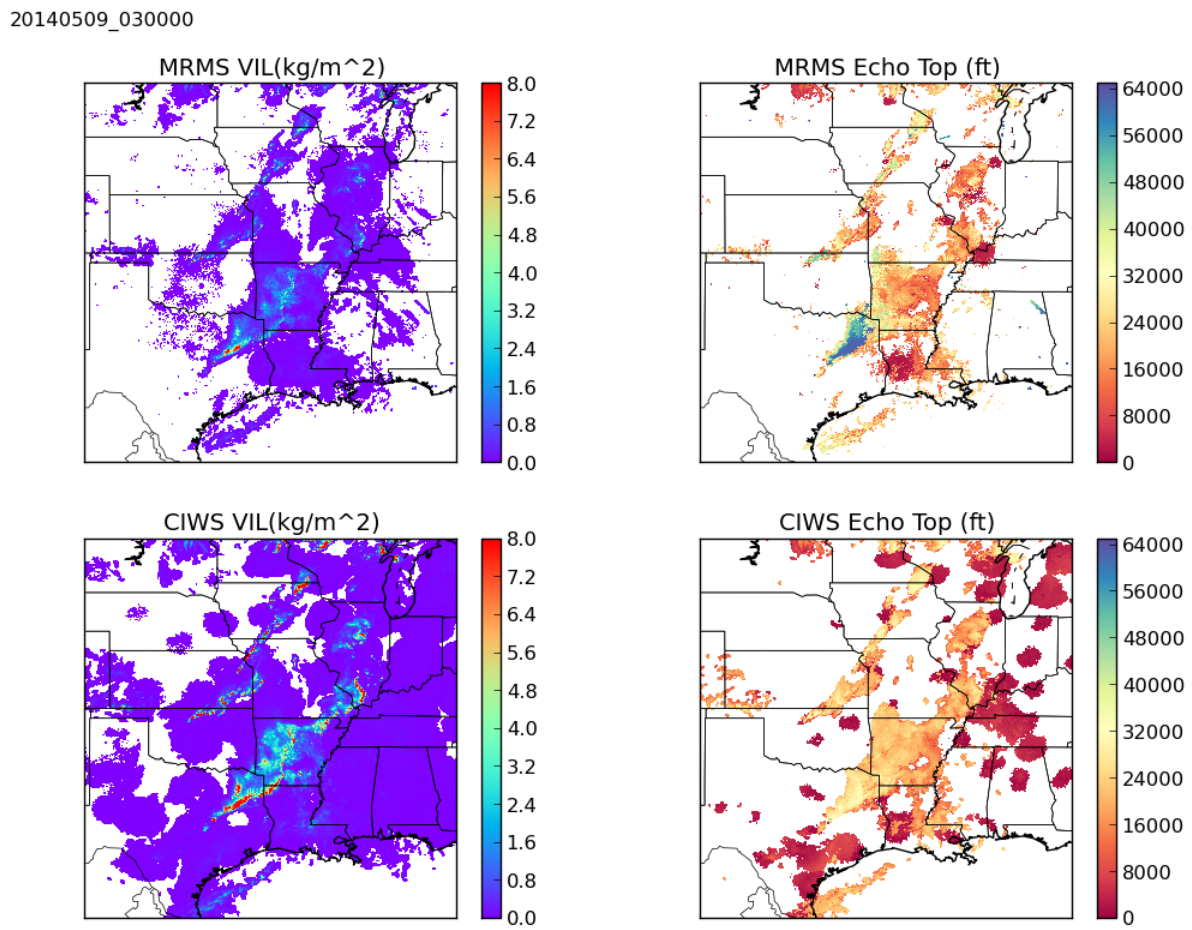


FIGURE 4.21: VIL (LEFT) AND ET (RIGHT) FROM MRMS (TOP) AND CIWS (BOTTOM) VALID AT 0300 UTC ON 9 MAY 2014.

4.5.2 12-13 May 2014

From the afternoon of 12 May 2014 into the early morning of 13 May 2014, there was a strong convective line extending from Lake Michigan to the Rio Grande. This line resulted in 43% delayed gate arrivals at DFW on 12 May, and 45% delayed gate arrivals at ORD (compared to 15% and 26% average in May 2014, respectively). An investigation of the VIL and ET fields from MRMS and CIWS at 0000 UTC on 13 May 2014 (Figure 4.22) shows that the MRMS VIL line to be less intense than in CIWS, while CIWS has an expansive near-zero VIL field. MRMS has higher ET along the convective line, in addition to high ET regions behind the line in areas without storms (e.g., central KS, north central TX).

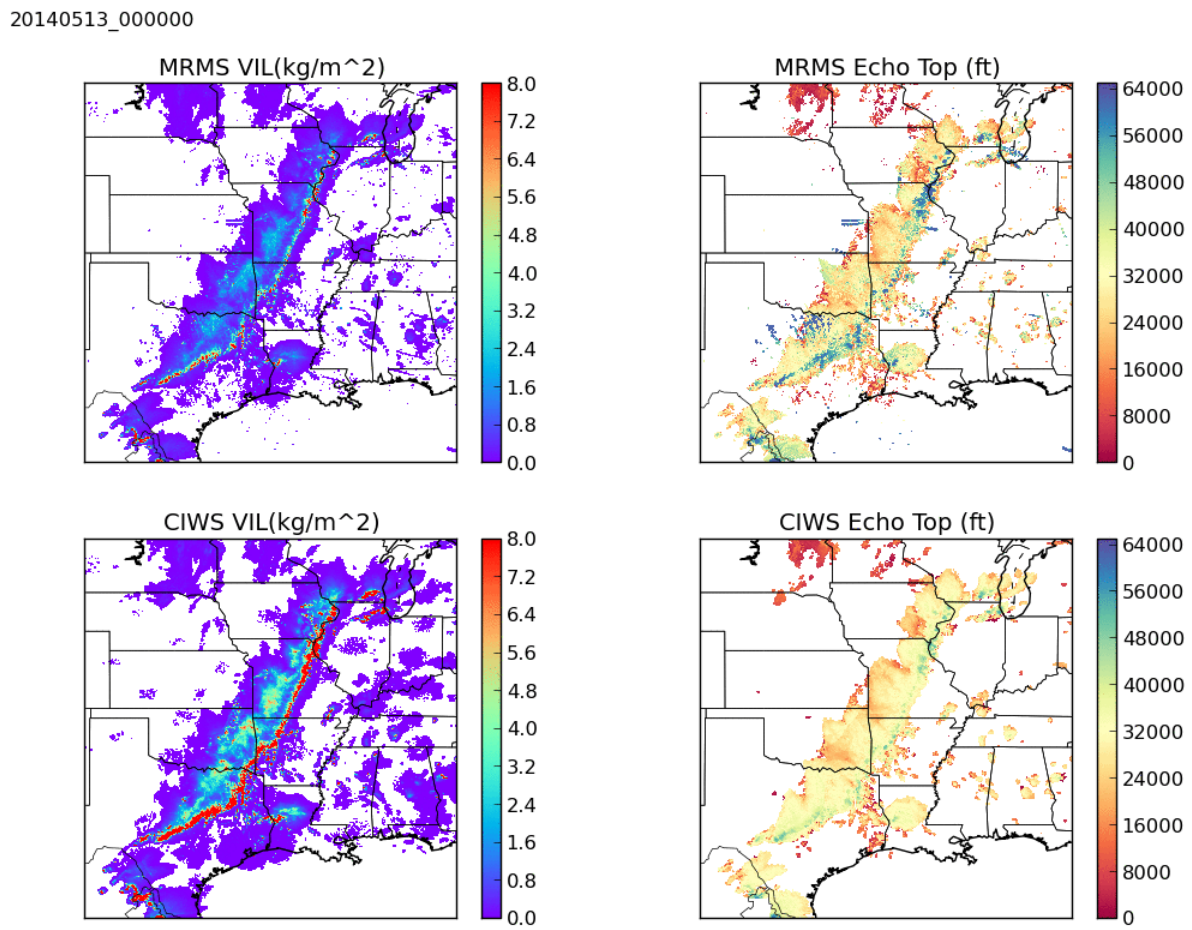


FIGURE 4.22: VIL (LEFT) AND ET (RIGHT) FROM MRMS (TOP) AND CIWS (BOTTOM) VALID AT 0000 UTC ON 13 MAY 2014.

Figure 4.23 shows the visible satellite image and METAR reports also valid at 0000 UTC on 13 May 2014. METARs suggest rain and thunderstorm activity trailing behind convective line in eastern Oklahoma and northeastern Texas, with CIWS showing more widespread high VIL values in these areas. In addition, cloudiness in Kansas, eastern Nebraska, and Iowa, identified as overcast in METAR, not represented in either MRMS or CIWS analyses.

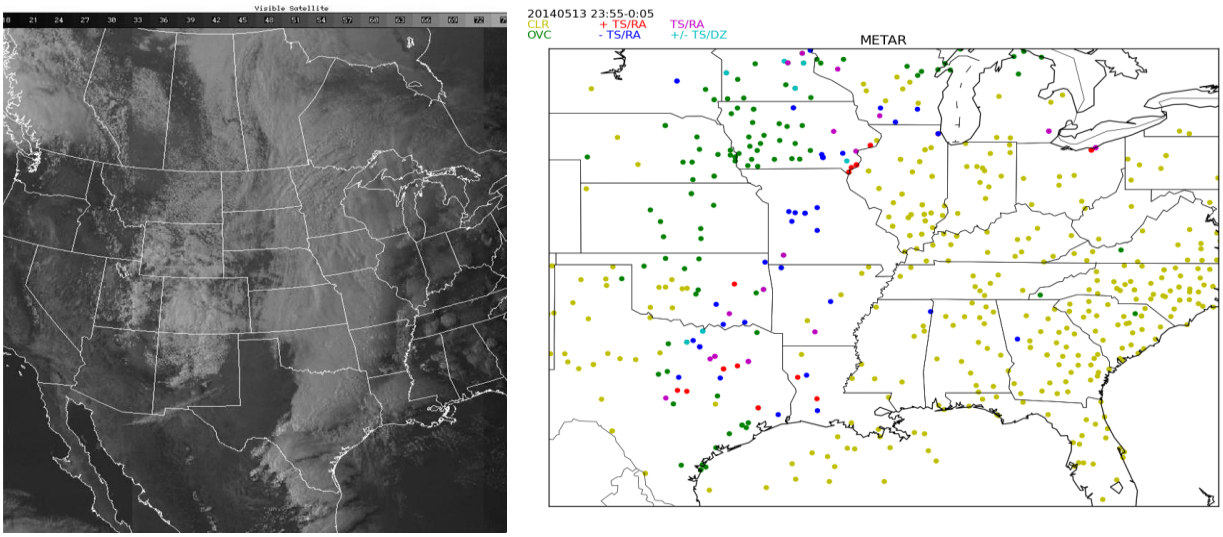


FIGURE 4.23: VISIBLE SATELLITE IMAGERY (LEFT) AND METAR REPORTS (RIGHT), BOTH VALID AT 0000 UTC ON 13 MAY 2014.

As was noted for the 08 May 2014 case, the combination of infrared satellite data with a sounding plot can allude to the more credible ET field. The infrared image valid at 2330 UTC on 12 May 2014 (Figure 4.24, left) indicates very cold cloud top temperatures of about -70 °C in the vicinity of Davenport, Iowa. The sounding from Davenport, IA at 0000 UTC on 13 May 2014 (Figure 4.24, right) indicates that -70 °C is approximately 50,000 ft above ground. Figure 4.22 shows MRMS ET to be approximately 60,000 ft in this region and CIWS ET to be approximately 50,000 ft. These results suggest the CIWS ET analysis is more accurate in this case.

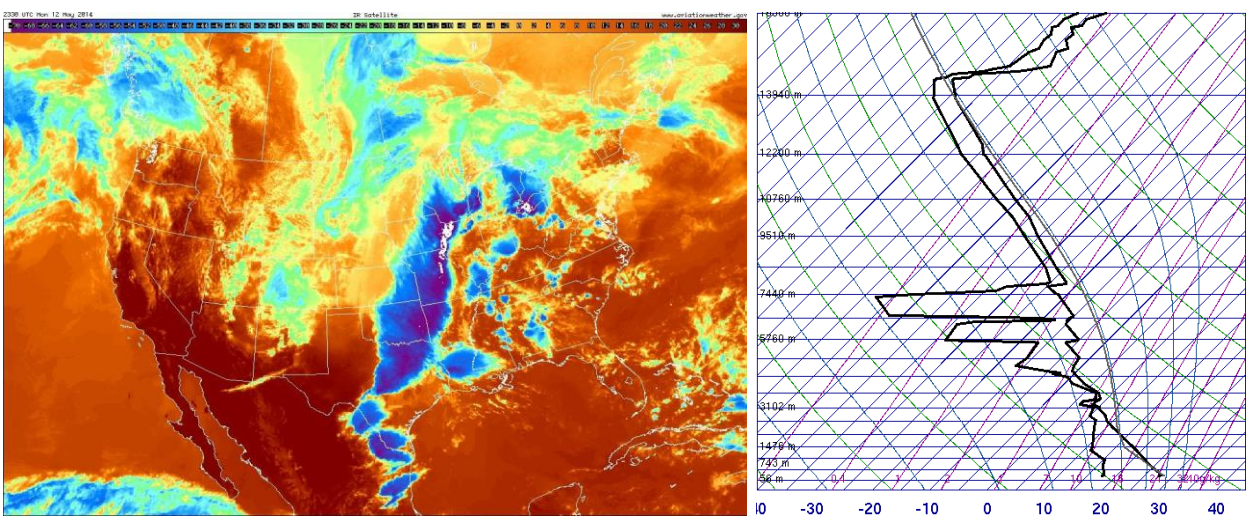


FIGURE 4.24: INFRARED SATELLITE IMAGERY VALID AT 2330 UTC ON 12 MAY 2014 (LEFT) AND DFW SOUNDING PLOT (RIGHT) VALID AT 0000 UTC ON 13 MAY 2014.

Though satellite and sounding data are helpful in assessing the ET fields, they do not provide a means of assessing the VIL field. To discern which VIL field is more representative, CIWS and MRMS are compared to a mosaic of four neighboring NEXRADs (KSRX, KSGF, KLZK, KSHV) that provide good coverage over western Arkansas. For this comparison (Figure 4.25), CIWS and MRMS

VIL fields are compared to the maximum-at-a-pixel VIL value (NEXRAD Max) using all four NEXRAD radars and the VIL value from the radar nearest the pixel (NEXRAD Nearest Neighbor). Note that CIWS uses the maximum plausible VIL in combining individual radars, and thus should resemble the maximum-at-a-pixel field, while MRMS uses a nearest-neighbor approach.

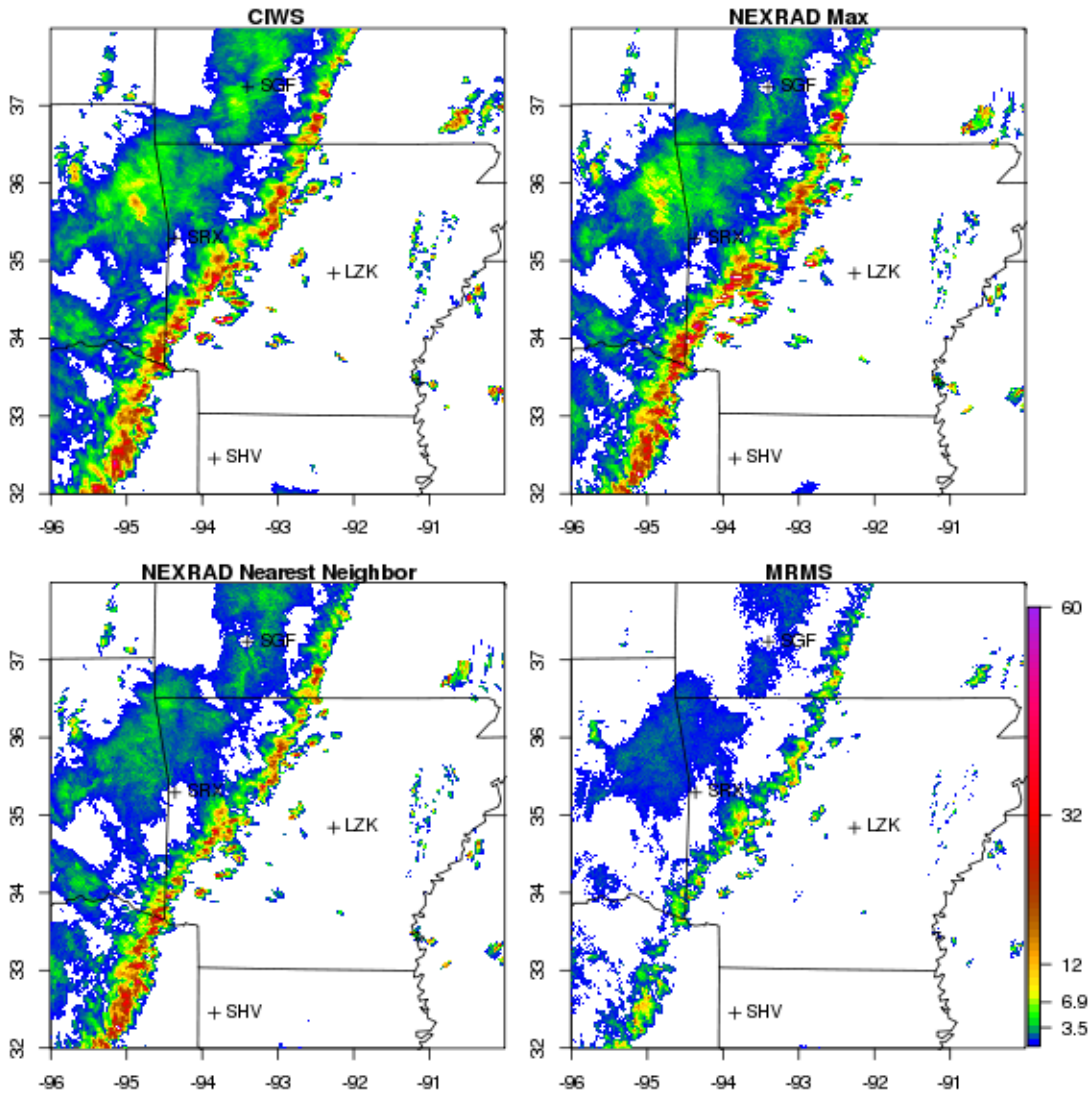


FIGURE 4.25: VERTICALLY INTEGRATED LIQUID (VIL) FIELDS FROM CIWS (TOP LEFT), NEXRAD MAX (TOP RIGHT), NEXRAD NEAREST NEIGHBOR (BOTTOM LEFT) AND MRMS (BOTTOM RIGHT) VALID AT 0030 UTC ON 13 MAY 2014. THE FOUR NEXRAD SITES USED IN THE MANUAL COMPOSITES ARE: CHAFFEE RIDGE, AR (KSRX), SPRINGFIELD, MO (KSGF), NORTH LITTLE ROCK, AR (KLZK) AND SHREVEPORT, LA (KSHV).

As seen in Figure 4.25, the CIWS VIL field matches very well with the maximum-at-a-pixel VIL; it is slightly less intense than the maximum in the main line, but slightly stronger in parts of the stratiform region behind the line (e.g., NW AR, NE TX). MRMS has significantly lower VIL compared to nearest neighbor NEXRAD field, despite the similarity it the MRMS mosaic algorithm. In Figure 4.26, the nearest neighbor image is replaced with the minimum-at-a-pixel VIL field (NEXRAD Min)

using all four NEXRAD radars. The MRMS VIL field more closely resembles the minimum VIL at-a-pixel field, with a less intense and reduced stratiform region.

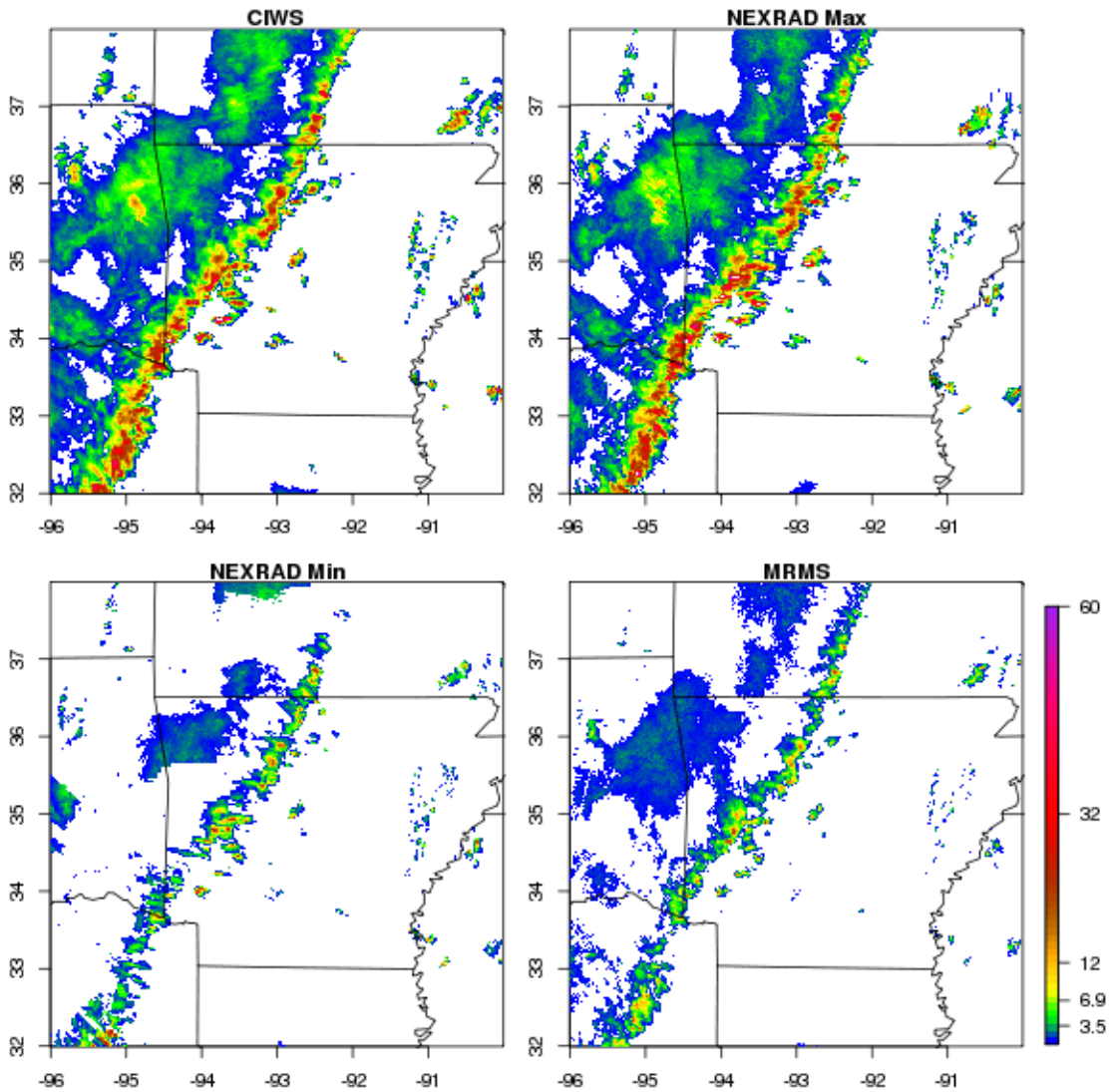


FIGURE 4.26: SAME AS FIGURE 4.25, EXCEPT NEXRAD MINIMUM IS SHOW IN THE BOTTOM LEFT.

5 CONCLUSIONS

The comparison of CIWS with MRMS (via a feed from the FAA William J. Hughes Technical Center) has shown several differences between the products. Assessment findings are as follows:

CIWS generally has a greater VIL extent and intensity than MRMS. Furthermore, given that MRMS fields have some unexpectedly high ET values, CIWS ET appears to give a more accurate representation than MRMS.

An investigation of forecast skill found CIWS forecasts are generally more similar to CIWS analyses than MRMS forecasts are to MRMS analyses for leads greater than 30 minutes (MRMS and CIWS forecasts are comparable at the 30 min lead).

A comparison to METAR observations of rain or of clear skies, found that when considering a threshold of VIL>0 kg/m^2, MRMS is more consistent with METAR reports than CIWS. CIWS, however, is more consistent with METAR reports than MRMS when considering a VIL threshold consistent with VIP level 1 (VIL>0.14 kg/m^2), except for reports of clear skies, where MRMS is more consistent.

Case studies indicate that the CIWS ET and VIL fields are a more conservative view of hazardous convection (identifies any potentially high VIL) as compared to individual radar observations than those of MRMS. More investigation is needed to understand the suitability of the MRMS VIL field as an indicator of air traffic impact.

In general, the differences between MRMS and CIWS are significant enough that one product likely cannot simply replace another without some adaptation in use. Some amount of training on the differences should be provided to users of these products.

6 REFERENCES

Benjamin, S. G., and Coauthors, 2007: From radar-enhanced RUC to the WRF-based Rapid Refresh. Preprints, 18th Conf. on Numerical Weather Prediction, Park City, UT, Amer. Meteor. Soc., J3.4.

Evans, J. E., Ducot, E. R., **Corridor Integrated Weather System**, MIT Lincoln Laboratory Journal, Volume 16, Number 1, 2006.

Layne, G.J. and S.A. Lack, 2010: Methods for estimating air traffic capacity reductions due to convective weather for verification. 14th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), Atlanta, GA, USA.

Langston, C., J. Zhang, and K. Howard, 2007: Four-Dimensional Dynamic Radar Mosaic. *J. Atmos. Oceanic Technol.*, **24**, 776-790.

Roberts, N.M., and H.W. Lean, 2008: Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events. *Mon. Wea. Rev.,* 136, 78-97.

Warning Decision Training Branch: Multi-Radar/Multi-Sensor (MRMS), accessed in 2014 at (http://www.wdtb.noaa.gov/courses/MRMS/ProductGuide/index.php)

7 APPENDIX A

A small comparison was performed while finalizing the report to determine if any differences existed between the MRMS product that was used for this assessment, as provided by the FAA Tech Center, and the MRMS as produced at NSSL. A cursory investigation of these two sources for the month of May 2014 suggests that there are some notable differences in the data between the two feeds.

Figure 7.1 compares the per-pixel aggregate counts of VIL >= 3.5 kg/m^2 and Echo Top >= 20,000 ft for the entire month of May 2014. While the NSSL version (top left) produces VIL of greater intensity and extent than the FAA Tech Center feed (top right), CIWS (bottom) has considerably greater VIL intensity and extent than both versions of MRMS. Case studies (not shown) were found to be consistent with climatological findings.

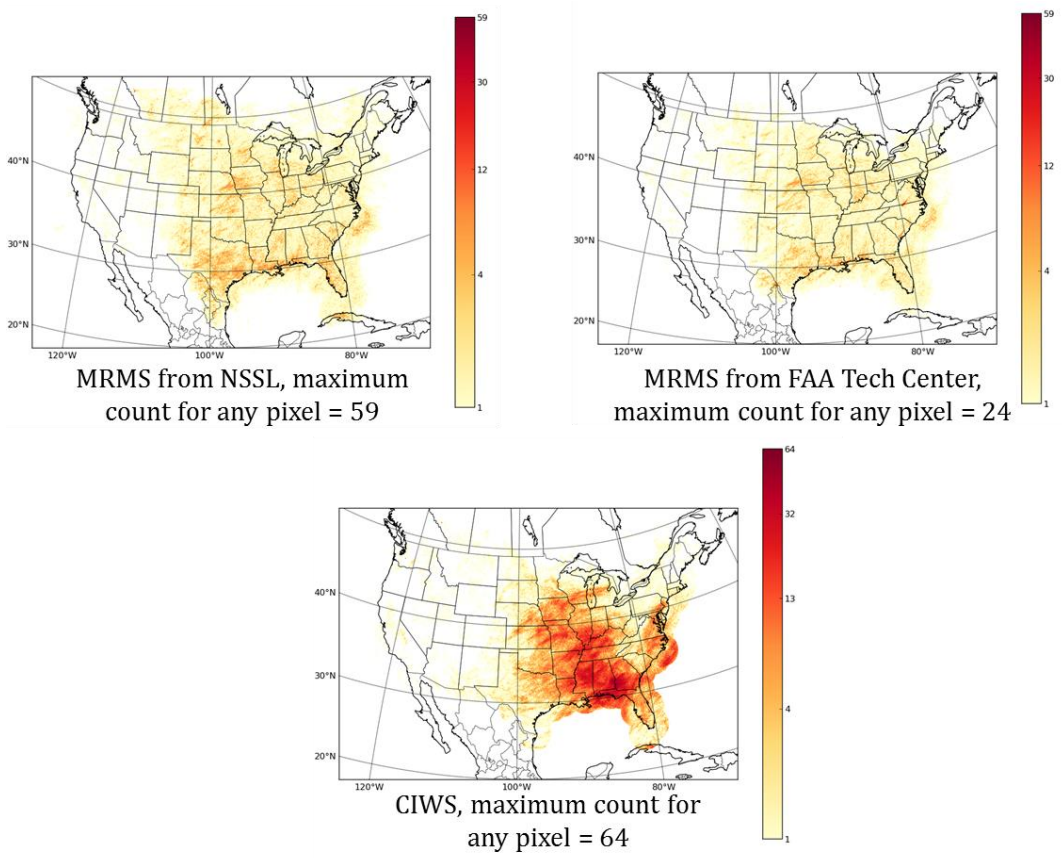


FIGURE 7.1: AGGREGATE COUNTS OF VIL >= 3.5 KG/M2 AND ECHO TOP >= 20,000FT FOR MAY 2014, FOR MRMS FROM THE NSSL FEED (TOP LEFT), MRMS FROM THE FAA TECH CENTER (TOP RIGHT), AND CIWS (BOTTOM). THE MAXIMUM COUNT AT ANY PIXEL FOR EACH SOURCE IS 59, 24, AND 64, RESPECTIVELY.

While the general conclusions would likely have held had the NSSL version been used for the assessment, it's possible that the degree to which they are true would have been different. As such, the conclusions presented in this assessment may not accurately represent the characteristics of the operational feed (NCEP).