1.5 RELATING A CONVECTIVE TRANSLATION METRIC TO CONVECTIVE IMPACT

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1. INTRODUCTION

Adverse weather imposes a major cost on U.S. aviation operations, but as much as two-thirds of the $28 billion annual losses are avoidable (FAA 2010). Reducing delays and their respective costs requires improved weather forecasts as well as improved integration of weather and air traffic information. Integration can be as simple as overlaying weather and air traffic data or can entail a complex melding of the two. However, to improve the utility of weather integration for determining impact, the weather information must first go through an intermediate step of translation. Weather translation changes current or future weather information into "operationally-meaningful weather-related values such as threshold events and/or characterized National Airspace System (NAS) constraints" (FAA 2010). In other words, the meteorological data is transformed from basic weather information into aviation-specific parameters, such as, snowfall rates at an airport converted to an arrival/departure rate change.

FAA NextGen plans call for a complete, automated integration of weather and aviation-specific information feeding decision support tools to develop Traffic Flow Management (TFM) solutions, such as the Airspace Flow Program (AFP). In the near- and mid-term time frames, however, humans will produce TFM solutions based on separate translated weather and air traffic information. In support of these activities, the Forecast Impact and Quality Assessment Section (FIQAS) of the Global Systems Division (GSD) of the Earth System Research Laboratory (ESRL) developed a weather translation, the Flow Constraint Index (FCI). In addition to its application to NextGen, the FCI is a useful tool for forecast current FIQAS verification efforts by placing disparate convective forecasts in a common framework for direct comparisons. Furthermore, the FCI ensures that the verification is accomplished in a framework relevant aviation operations.

The goal of this study is to establish the operational relevance of the FCI by demonstrating that it contains sufficient information to skillfully identify the issuance of AFPs, further validating its usefulness in verification methodologies for assessing the quality of convective forecasts for strategic traffic flow planning.

The Flow Constraint Index is presented in Section 2, followed by a description of AFPs in Section 3. Section 4 summarizes the methodology used to establish the relationship between the FCI and AFPs. The results are presented and summarized in Section 5. Finally, the conclusions and ongoing work is available in Section 6.

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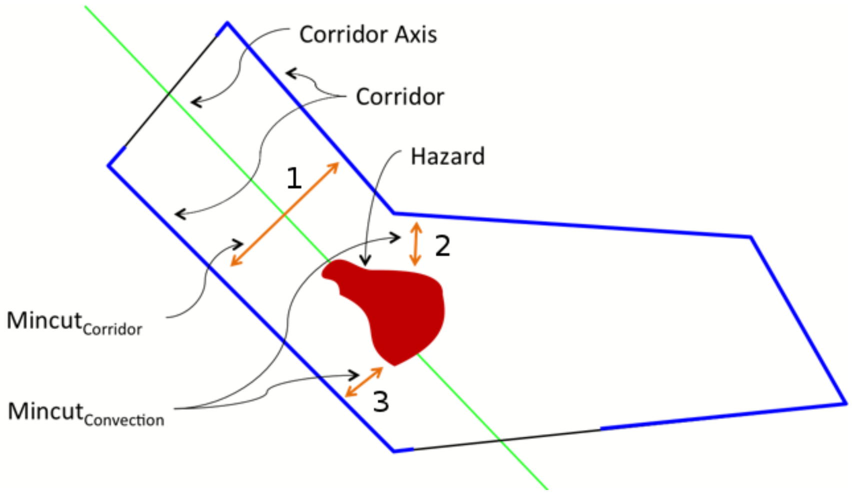

Figure 1. Conceptual model of the Flow Constraint Index. Blue lines represent the corridor boundaries. The red area denotes an area of hazardous weather. Arrow 1 represents the distance across the corridor in the absence of hazards. Arrows 2 and 3 show the distance across the available airspace around a hazard. The flow constraint is a function of the ratio of these two distances.

2. FLOW CONSTRAINT INDEX

An overview of the FCI is provided in this section. An additional overview of this approach and its usefulness for verification can be found in Layne and Lack, 2010.

To begin, consider a constraint field representing potential air traffic flow restriction through a portion of the airspace due to the presence of a particular hazard, such as convection. The traffic flow constraint is determined using a class of mathematical algorithms known as the Mincut Max-flow (MCMF), developed as a part of graph theory (Ford and Fulkerson, 1956). The FCI is a specific implementation of the MCMF approach for weather, where weather can be either forecasted or observed. Any given portion of the airspace can be treated as a corridor through which air traffic travels; the sides of the corridor comprise one or more connected line segments as part of a geometric shape (Fig. 1). Significant weather located within the corridor will impact the flow of traffic through the corridor. The FCI is a measure of the reduction in the potential flow through the corridor and is independent of the actual traffic flow.

To calculate FCI given a polygon defining the bounds of a corridor, Mincut calculations are performed for the corridor itself and for the corridor with hazards included. These two Mincut values are then combined to produce the FCI, according to (1).

$$\textbf{FCI} = \textbf{1} - \textbf{Mincut}_{\textbf{hazard}}/\textbf{Mincut}_{\textbf{corridor}} \quad \textbf{(1)}$$

$Mincut_{hazard}$ is derived from the paths between the sides of the corridors and any intervening weather hazards (e.g., arrows 2 and 3 in Fig. 1), and $Mincut_{corridor}$ is derived from the unconstrained corridor cross section (e.g., arrow 1 in Fig. 1). In the absence of weather, the ratio is 1.0 and FCI is 0.0, indicating no constraint. If weather extends across the entire width of the corridor, the ratio is 0.0 and FCI is 1.0 indicating complete blockage. Note that the restricted portion of the corridor affects the maximum potential flow through the corridor.

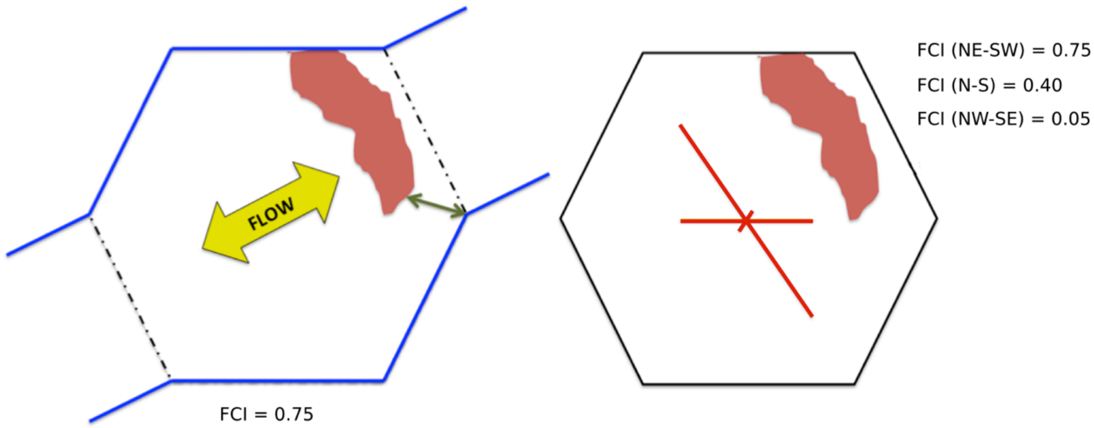

Figure 2. Illustration of the FCI concept for a hexagonal geometry. The hexagon contains three separate corridors, one for each pair of opposing faces: traffic moving from northeast to southwest, from north to south, and from northwest to southeast. (The FCI is identical for traffic flowing in the opposite directions.). A weather hazard is denoted by the red area. The green arrow (left) shows the mincut distance for the northeast-to-southwest corridor. The length of the red lines (right; as a fraction of the total corner-to-corner distance) represent the FCI value for traffic moving perpendicular to the line.

For this study, the FCI is applied to hazard fields derived from the Vertically Integrated Liquid content (VIL) provided by the Corridor Integrated Weather System (CIWS). Hazards are defined as regions of VIL ≥ 3.5 km m^{-2}, which is approximately 40 dBZ. Corridors are created using hexagon shapes approximately the size of an Air Route Traffic Control Center (ARTCC) region, although any shape or size object can be applied. Figure 2 shows an example of the hexagonal shape. Removing a pair of opposing sides of the hexagon creates a corridor; the flow restriction is determined for each of the three corridors, yielding three FCI values for the hexagon. The elongated area of convection, shown in red in Fig. 2 and oriented from northwest to southeast, restricts 75% of the airspace for planes attempting to travel from the southwest the northeast. Because of the northwest-southeast orientation and location of the convection, less than half of the potential flow of the north-south corridor is constrained, and nearly zero constraint is found for traffic moving from northwest to southeast. Each of the three FCI values are represented by the length of the lines, as a fraction of the distance from opposing corners plotted within the hexagon (see right side of Fig. 2).

3. AIRSPACE FLOW PROGRAMS

In order to manage traffic within airspace that has been constrained by weather, the Flow Evaluation Team (FET) developed a traffic management mechanism called Airspace Flow Programs (AFP) used to efficiently throttle air traffic through the NAS (FAA/CDM 2005). AFPs are produced by the Air Traffic Control Systems Command Center (ATCSCC) and contain boundaries used to govern the number of flights entering or exiting a constrained airspace. FCAA05, FCAA06, and FCAA08 (hereafter referred to as A05, A06, and A08) are three commonly used AFPs for addressing weather impacting travel in and out of the northeast. The western boundary of the Cleveland ARTCC (ZOB) and eastern boundary of the Indianapolis ARTCCC (ZID) define A05 (Fig. 3, top), which is used to manage east/west travel. A06 and A08 are used to manage north/south traffic, where A06 is defined by the western and southern boundary of the Washington ARTCC (ZDC) and A08 is located further north following the western boundary of the ZDC ARTCC into southern West Virginia and east through central Virginia (Fig. 3, middle and bottom). Weather in the Ohio Valley will typically compel the use of one or more of these AFPs.

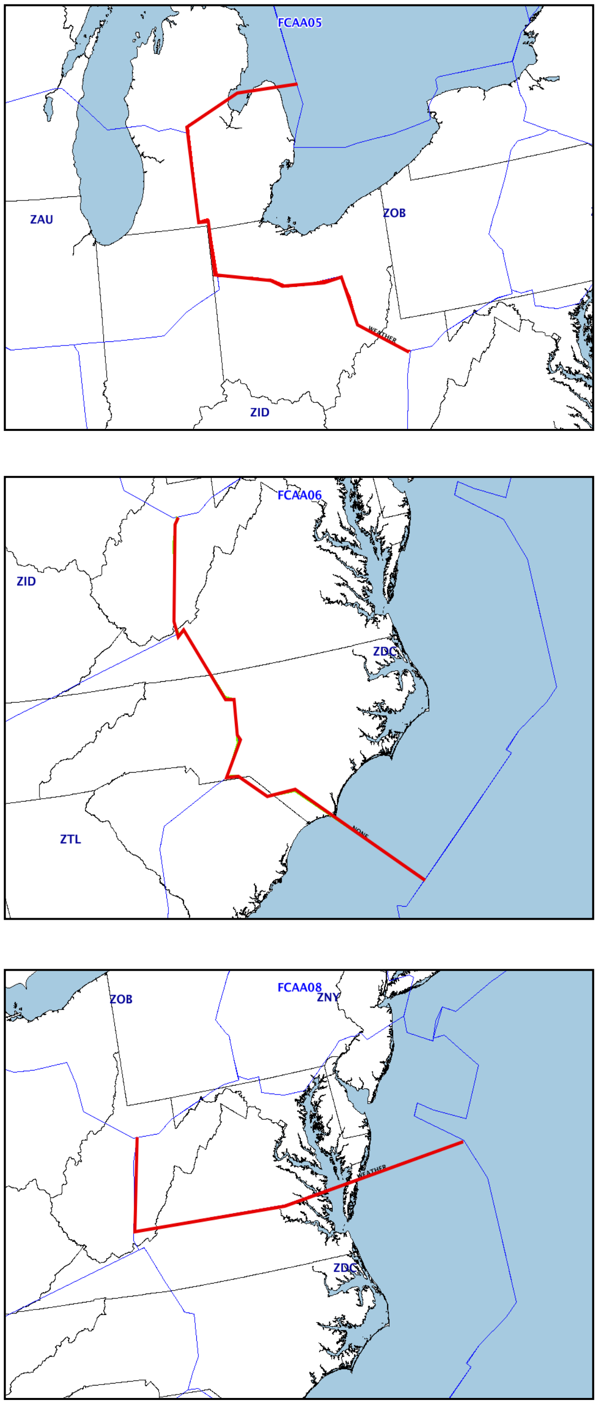

Figure 3. Red lines mark the FCAA05 (top), FCAA06 (middle), and FCAA08 (bottom) boundaries.

4. METHODOLOGY

The methodology used to demonstrate a relationship between the FCI and the AFP described here required some preliminary work. First, in order to establish a base of knowledge, an initial investigation into the correspondence between weather forecasts, observations, and AFPs was completed. Second, several classification models were assessed for use in determining a relationship between the FCI and the AFPs. Third, characteristics of the AFPs were analyzed to identify relevant stratifications for use in the classification model.

AFP data were obtained for June-August 2010/11. Only AFPs for which the “Impacting Condition” included the word “Thunderstorm” are considered. For this study, the effective states of A05, A06, and A08 are included at specific hours during what is considered the core convective period (1700-2300 UTC). The effective state refers to the realized usage of these AFPs, that is, if an A05 was scheduled to be in effect from 1700 to 2100 UTC but was canceled at 1900 UTC, the hours following 1900 UTC are excluded from the AFP duration.

Only certain hours of AFP issuances were included in the study. Even hours were eliminated to reduce temporal dependence. Additionally, AFPs for the hours preceding 1700 UTC and following 2300 UTC were excluded, as they are believed to have more dependency on AFPs during the core convective hours rather than on the existence of weather at that time. For example, AFPs are often in effect earlier than is warranted by the weather, possibly to get the air traffic flow “in front of the storm” and not risk unnecessarily tactical challenges. Likewise, when adverse weather persists, AFPs are sometimes removed, perhaps to address the backlog of flights. Therefore, only the core hours of 1700, 1900, 2100, and 2300 UTC are included in the study, resulting in nearly 730 hours of independent truth data (represented by CIWS VIL) to be used for this assessment.

4.1 An Initial Investigation of Weather and AFPs

4.1.1 FCI-translated Forecasts and the AFPs

Investigation to identify a relationship between FCI and AFPs began with a comparison of FCI-translated forecasts and AFP issuances. The preliminary results revealed no consistent pattern between them. This result was expected since the ATCSCC uses graphical forecasts from multiple sources, forecaster discussions, observational trends, and other weather information.

4.1.2 FCI-translated Observations and AFPs

In light of our findings from the investigation of FCI-translated forecasts and AFPs (summarized in Section 4.1.1), a relationship between the FCI-translated observed weather (i.e., FCI applied to the CIWS VIL field) and AFPs was investigated. Since it is assumed that the ATCSCC traffic flow managers are skillful at issuing AFPs, AFPs should correlate to the actual weather as measured through the translated VIL observations. However, the process for associating AFPs to observation-based FCI fields poses some challenges: the use of AFPs is a human decision based on guidelines that can be subjective, the forecasts informing the decision to issue AFPs contain inherent uncertainties, and the AFPs are a relatively new tool therefore its usage continues to evolve. Examples of the AFP evolution are identified by differences in weather scenarios that warranted the issuance of AFPs in 2010 versus 2011. For instance, some of our initial primitive classification models used to test for an FCI-AFP relationship successfully classified events for either 2010 or 2011, but not both. In addition, new AFP boundaries were introduced in 2011, indicating that the weather scenarios triggering AFPs in 2010 may be different than those used to trigger AFPs in 2011. These findings suggest differences in either the weather patterns between 2010 and 2011 or the decision making process behind the AFP issuances.

4.2 Classification Model

Many potential classification models and approaches for demonstrating the relationship between FCI and AFPs exist. As part of this work, the Random Forest and Support Vector Machine were considered, but performed poorly at classifying events as AFP issuances, due to their rare occurrence in overall traffic operations. Since our goal is to merely show that a relationship between the FCI and the AFP exists, a simple classification approach where a threshold is applied to a weighted sum of an input vector is used. Within this classification approach, the input vector consists of the FCI scores for the three corridors for each of the ARTCC-size hexagons in the eastern United States. Since the computational resources required to run a full set of permutations for this input vector are prohibitive, a two-step approach is applied. The first step finds the optimal threshold and weights used to combine the FCI values from the three directions for each hexagon, resulting in a single value for each of the hexagons. The second step finds an optimal combination of the values from the hexagons obtained from the first step, producing a single grid-summary FCI value. Breaking the problem into these two steps may potentially decrease the classification accuracy, but the classification model still performs adequately well (as shown by results in section 5).

The Critical Success Index (CSI) was selected as the skill measure to optimize the classification model. A large CSI value implies a strong association between FCIs and AFPs. The CSI score is used to measure the event space and is not applied to the non-event (i.e., no AFP issued) space. A threshold is applied to the grid-summary FCI value resulting in a deterministic indicator of AFPs. As a reminder, our goal is not to develop a predictor of AFPs for future weather situations, but to demonstrate that the FCI translation contains sufficient information to identify recorded AFPs.

4.3 AFP Characteristics and Their Influences on the Classification Model

Prior to stratifying the AFPs by their characteristics, the classification approaches that were initially tested, along with the methodology chosen as described in section 4.2, indicated poor agreement between the FCI and the AFPs, warranting further investigation of the AFP characteristics. Following are some of the characteristics observed through our investigation and their resulting influences on the classification model.

AFPs were not issued in response to impactful weather alone, but when impactful weather could render the airspace capacity insufficient to meet the demand. An example of this behavior was that AFPs were never issued on Saturdays (a low air traffic day), despite the occurrence of some significant Saturday weather events. Also, AFPs were rarely issued during the late afternoon if weather did not initiate earlier in the day; that is, without the impacts of earlier weather a short time before traffic demand abated for the evening, tactical TFM decisions were used to deal with the resulting traffic issues instead. In general, it is apparent that AFP directives are based on airspace demand and air space capacity. Since the demand and capacity vary by day of week and hour of day, the observation and AFP data were stratified as such, so that each hour (1700, 1900, 2100, and 2300 UTC) for each day of the week was a separate stratification for the model. Applying these stratifications resulted in 28 different sub-mappings within the classification model, that is, a separate model was determined for each hour of each day.

It was additionally observed that the issuance of an A05 almost always occurred in conjunction with an A06 or A08. The East/West routes out of the Northeast are managed with the use of A05, and due to the significant traffic demand it is often necessary to enact an A06 or A08 to prevent excessive traffic from rerouting around the southern end of the A05 boundary, which would impact the North/South routes. It is less common, but may have still occurred, that A05 was enacted to address reroutes as a result of A06 or A08. In summary, although the occurrence of A05 is not independent of A06 and A08, the classification model was run separately on each. To accommodate the issuance dependency, weather in the region encompassing an area approximated by the Golden Triangle (the area defined by Newark, Atlanta, and Chicago O'Hare) was considered when running the model for each AFP region.

5. RESULTS

Following is a discussion of the resulting CSI scores from the classification model. Scores are provided separately for each of A05, A06, and A08. The overall skill for each AFP is an aggregation of the skill of each of the 28 sub-mappings defined by the hour and day stratifications. The CSI obtained from the aggregated model for A05 was 0.90, with 0.96 and 0.88 obtained for A06 and A08, respectively. The high score for A06 occurred for a small sample of issuances (only 3 percent), while the event frequency for A05 and A08 AFPs is approximately 10 percent.

Table 1. Contingency table for classification of FCAA05 events.

		FCAA05 Issued	
		Yes	No
FCI Predicted FCAA05	Yes	66	3
	No	4	653

Table 1 shows the full contingency table for the model classification of A05 events. Note that there are only seven misclassifications, and at least some of those appear to result from a lack of correspondence between the observed weather and the AFP. For example, an AFP was issued on 18 August 2011, but very little convection appears anywhere in the Northeast (Fig. 4). Radar trends (not shown) and CCFP forecasts (not shown) both indicated the potential for convective lines to form along the Great Lakes into OH and from southeast NY into western NC, but neither line actually developed.

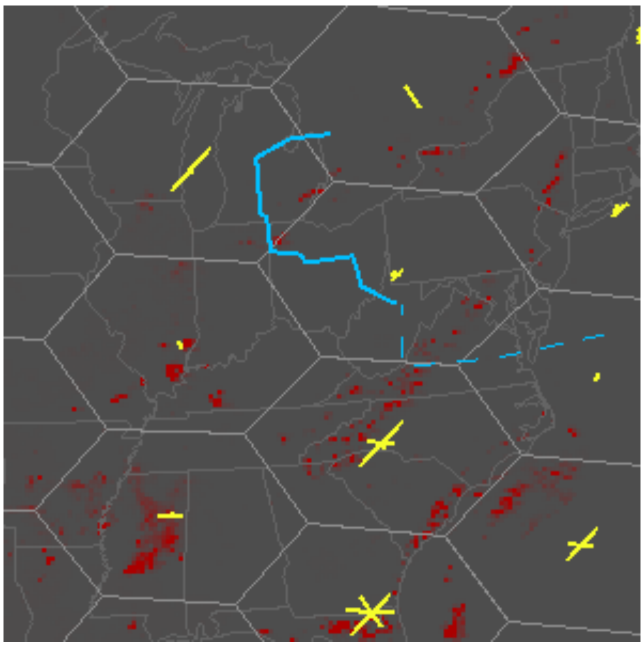

Figure 4. CIWS VIL 3.5 field (red), FCI (yellow lines, length of line represents extent of constraint), A05 (solid blue line) and A08 (dashed blue line) for 1900 UTC 18 August 2011.

Contingency tables are constructed for A06 (Table 2) and A08 (Table 3) issuances, as well. There are a total of seventeen off-diagonal elements (i.e., misclassifications) between the three tables. Fourteen (82%) of those misclassifications occur on either Thursday or Sunday. A preponderance of AFPs were issued on Thursdays suggesting a disproportionate level of active weather. The higher misclassification rate on Sundays may result from higher traffic volumes; with the system operating near capacity, operators may have a lower threshold for issuing AFPs. Three of the misses occurred on a single day (12 June, 2011; not shown) in which storms initiated, but failed to organize.

Table 2. As in Table1, but for FCAA06 events.

		FCAA06 Issued	
		Yes	No
FCI Predicted A06	Yes	24	1
	No	0	701

Table 3. As in Table 1, but for FCAA08 events.

		FCAA08 Issued	
		Yes	No
FCI Predicted A08	Yes	65	7
	No	2	652

To ensure that the chosen classification model isn't under-constrained, that is, it is able to correctly classify any training set, significance testing was performed. Ideally, the model skill would have been assessed with the use of cross validation; however, given the small sample, the rareness of the event, and the stratifications, cross-validation was not practicable. Alternatively, we tested the model's ability to map randomly generated training sets. Within each stratification, an FCI case was randomly associated with an AFP issuance. For example, each Tuesday 2100 UTC AFP state (yes/no) was randomly paired with any Tuesday 2100 UTC FCI value. This random association was repeated one hundred times and the model's ability to skillfully classify AFPs was recorded, again using CSI as the measure of skill.

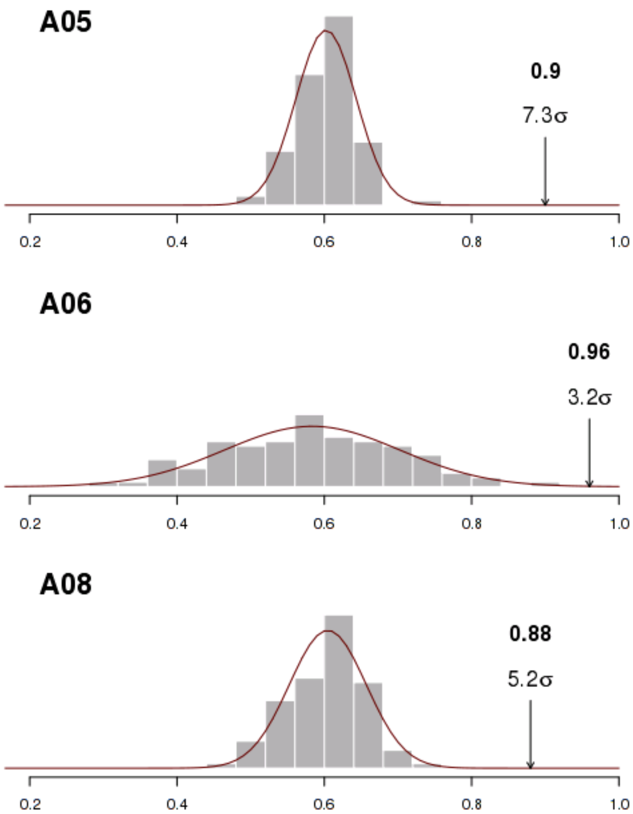

Figure 5. Histograms (gray bars) and fitted normal distribution (red line) for the CSI of the random pairings of FCI fields and AFP states. Bold numbers denote the skill of the classification model for the true pairings. Light numbers denote the number of standard deviations between the true model skill and the mean of the corresponding distribution.

The distribution of random skill is approximated by a normal distribution (Fig. 5). The CSI for A05, A06, and A08 mapping are 7.3, 3.2, and 5.2 standard deviations away from the mean value of the distribution of the random data sets. Noting that 99.7% of a normal distribution is within three standard deviations of the mean, the skill of the classification model is significantly distinguished from that of randomly determined skill, indicating the model is indeed exhibiting true skill in identifying critical weather impact relevant to the use of FCAs.

6. CONCLUSIONS AND ONGOING WORK

The goal of this study was to assess the existence of a relationship between translated weather as represented by the FCI and AFPs. A classification model was used to effectively demonstrate a close relationship between the two. Sensitivity testing shows the close association between them is not spurious.

With a larger dataset and the addition of more detailed traffic flow information, it would be possible to explore the use of FCI as an input to decision support tools. Furthermore, having established the connection between FCI and an operational traffic initiative, FCI is validated as a useful verification technique: the closer a forecast-based FCI is to the FCI from the corresponding analysis, the more useful the forecast is from an operational perspective. This is true for an individual forecast or a synthesis of multiple forecasts. Additionally, weather translation, such as FCI, allows one to place different types of forecasts (e.g., probabilistic, categorical, and deterministic) in a common framework, making performance comparisons as well as forecast synthesis more practical.

REFERENCES

FAA/CDM, 2005: Operational concept for airspace flow programs (AFP). 21 pp.

FAA/AJP, 2010: ATM weather integration plan overview and weather translation description. 22 pp.

Ford, L.R., Jr., and D.R. Fulkerson, 1956: Maximal flow through a network. *Canadian Journal of Mathematics,* **8,** 399-404.

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