2.5 TRANSLATING CONVECTIVE WEATHER FORECASTS INTO STRATEGIC TRAFFIC MANAGEMENT DECISION AIDS*

Michael P Matthews†, Joseph Venuti and Rich DeLaura
MIT Lincoln Laboratory, Lexington, MA 02420, USA

1. INTRODUCTION

Weather accounts for over 70% of the delay in the US National Airspace System (NAS) and convective weather accounts for 60% of these weather delays [1]. To try and mitigate these delays, forecasts of convective weather are used by traffic flow managers to attempt to match traffic demand to capacity constraints of specific air traffic resources such as en route flows or departure fixes via a strategic management plan. Traffic demand for impacted resources is managed through the application of traffic management initiatives (TMI) that either completely remove demand from an impacted airspace resource or that reduce demand by delaying the departure of flights filed through the impacted airspace. Typical strategic TMI programs used by the Air Traffic Managers of today are mandatory playbook reroutes, Ground Delay Programs (GDP) and Airspace Flow Programs (AFP) as shown in figure 1. Since these TMIs require the pre-departure management of demand, the lead time for such decisions may be several hours in advance of the event onset to ensure that the TMI is in place soon enough to capture demand prior to departure. This also allows airline operators to plan for the schedule and fueling consequences of the TMI.

For successful planning of TMIs, decision makers require weather forecasts of the impacted airspace between 2 and 8 hours in advance of the event to set the critical parameters of the TMI such as start time, duration and maximum flow reduction. Several weather-only convective forecasts are available to the traffic planner in the strategic time domain such as the Consolidated Storm Prediction for Aviation (CoSPA) [2], Short Range Ensemble Forecast (SREF) [3] and Collaborative Convective Forecast Product (CCFP) [4]. However, these forecasts provide little guidance about aviation impact on the air traffic resources and the precise location, severity, scale, and timing of operationally significant storms and the human response to those storms can be notoriously difficult to predict. Therefore, the decision maker is left to make critical TMI decisions based on a subjective assessment of potentially conflicting weather forecast information (figure 2).

The lack of an explicit translation of weather forecasts into resource constraints is a shortfall in the current weather information available to air traffic managers for strategic traffic flow management. There are several consequences of this shortfall. First, without an explicit translation there is a lack of an operationally relevant methodology to assess weather forecast resource impact and overall forecast performance. Each participant (e.g., Air Traffic Control System Command Center (ATCSCC), Air Route Traffic Control Center (ARTCC) Traffic Manager Unit (TMU) and Airline Operations Center (AOC)) comes into the collaborative strategic planning process with their own set of operational objectives, favorite forecast information, risk tolerance, etc. This wide and often divergent range of opinions and goals must somehow be melded into a plan of action. Without shared objective forecasts of weather impacts and estimates of decision risk, there is little common ground on which to base discussions about the best plan of action that addresses the different legitimate concerns of stakeholders. Second, the utility of convective weather forecasts is directly related to the quality of decisions and NAS performance outcomes that the forecasts can support. The definition of explicit, validated weather translations provides an objective and operationally relevant measure of truth against which forecasts can be compared. Without translation-based forecast evaluations, it is

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† *Corresponding author address*: Michael P Matthews, MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9185; e-mail: mpm@ll.mit.edu

difficult to determine how much of an operational shortfall in convective weather mitigation is due to poor weather forecasts and how much is the result of poor interpretation and application of forecast information.

Previous efforts to estimate convective weather impacts have focused either on individual Air Traffic Control (ATC) sectors [5] or sector-traversing flows [6]. Such resources are important to tactical operations, as traffic managers seek to avoid sector overloads that can result in sector closures and excessive airborne holding. However, sector-level impacts are a poor match for strategic planning. Strategic planners usually focus on key, large-scale traffic flows that traverse oft-congested en route airspace (e.g. ARTCCs) or that carry traffic to or from transition airspace for busy metroplexes. Furthermore, the precision of convective weather forecast needed to estimate sector capacities is unachievable in the strategic planning time horizon.

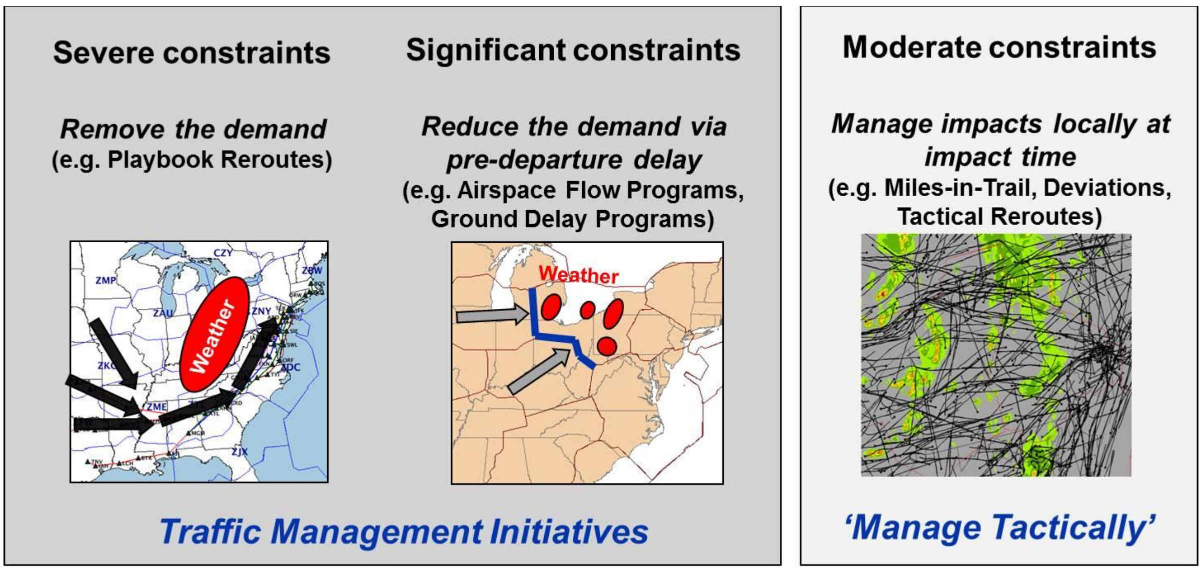

Figure 1. Relationship between weather-related capacity constraints and TMI to manage demand.

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In section 2, we review a model developed at MIT Lincoln Laboratory [7] that translates forecasts of Vertical Integrated Liquid (VIL) (a measure of precipitation intensity) and radar echo tops (a measure of storm height and convective vigor) into a prediction of airspace permeability which is used to estimate the impact of the convective weather on strategic traffic flows. In section 3 we will expand on the validation of the model using weather impacted days from the summer of 2014 and a larger set of operationally significant air traffic resources to explore the relationship between permeability and traffic flow capacity. Section 4 will present the two operational case days in which the air traffic planners at the ATCSCC were provided with guidance from the translation model. Section 5 will conclude with recommendations for future work to enhance the validation and operational usefulness of the model.

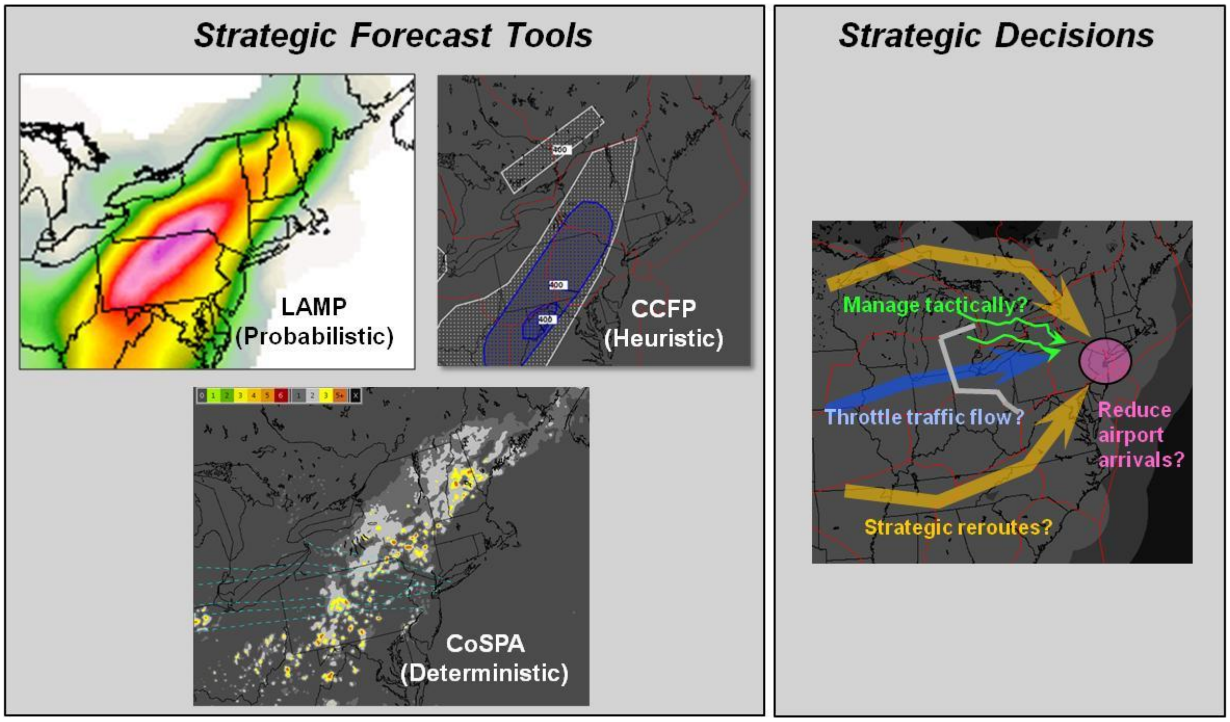

Figure 2. Illustration of current convective weather forecast products and the strategic decisions that traffic planners must make.

2. MODEL OVERVIEW

The translation of convective weather forecasts into an airspace impact classification began with a translation of weather truth data into an estimate of airspace permeability. The airspace permeability was then validated with an observed real-time operational flow rate that was assumed to represent, to the first order, the operational impact of convective weather on the air traffic operations. Validation showed good agreement between the permeability estimate and the measured flow rates. It was then surmised that the permeability estimate could be used as a basis of a weather impact classification for airspace that can be calibrated to specific decision and airspace constraints.

The translation model is based upon the Weather Avoidance Fields (WAF) developed as part of the Convective Weather Avoidance Model (CWAM) [8], the definition of airspace resources that are operationally significant and whose capacities are measureable, and the assessment of operational impact of weather on a trajectory. The initial development of the model focused on the region to the west of New York City where major arrival and departure routes into and out of the major NY metro airports transition between the Cleveland ARTCC (ZOB) and the New York ARTCC (ZNY).

An example of the airspace resource definition for this flow is shown in figure 3. The resource definition consisted of three components: airspace crossing; airspace boundary; and airspace traversing trajectories, all of which define a strategic flow through the airspace. The airspace crossing represents an imaginary line for which all aircraft in the strategic flow that traverse this resource will intersect. The airspace boundary represents the region for which the model will evaluate the weather characteristics to estimate the permeability. Finally, the airspace traversing trajectories represent notional routes perpendicular to the aircraft crossing that are possible trajectories through the weather.

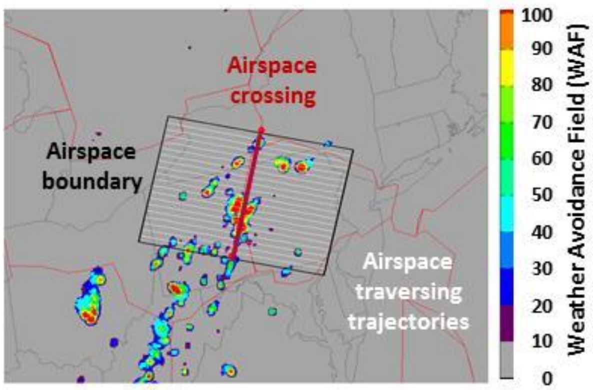

Figure 3. Illustration of WAF (color) and airspace resource definition for the ZOB / ZNY strategic flow.

The method of assessing the impact of the weather on a trajectory takes into account the scale and severity of storms that impact the flight trajectory. Storm scale is represented by the length of time that a trajectory spends inside a Convective Weather Avoidance Polygon [9]. Severity is represented by maximum blockage [10] calculated along the trajectory. Each notional route is then assigned an impact of RED (impassable), YELLOW (uncertain), DARK GREEN (passable with acceptable storm-avoiding deviations), or GREEN (passable) based on the two-dimensional heuristic trajectory impact model as shown in figure 4.

Finally, the permeability of the airspace, or the availability of passable corridors that traverse the airspace is estimated by taking a weighted average of the trajectory impacts for all the notional routes that traverse the airspace. The four impact categories are weighted as follows: GREEN routes are weighted by 1.0 (100% probability of successfully flying route), DARK GREEN by 0.8 (20% impacted), YELLOW by 0.5 (50% impacted), and RED by 0.0 (route is completely blocked). The airspace classification is then scaled into a percentage.

The model was shown to have good agreement between the estimated permeability and the observed flow rates for ten moderate to severe weather impacted and 31 minimal to no impact days from the summer of 2013. However, during some periods, observed flows may not accurately reflect the flow capacity. Upstream or downstream impacts may reduce the flow in un-impacted airspace simply because the aircraft are unable to reach the airspace due to other constraints. Strategic TMIs implemented by traffic flow managers may reduce the demand on airspace unnecessarily, resulting in observed flows that are less than the achievable capacity. Conversely, higher than preferred observed traffic may be occurring through heavily impacted airspace if creative but difficult to sustain tactical operations are undertaken by air traffic controllers to reduce a large inventory of airborne aircraft that were 'trapped' in the airspace or flow when unanticipated convective impacts occurred. In all of these instances, the observed traffic flow may not represent a true estimate of the achievable, sustainable flow capacity across the impacted airspace.

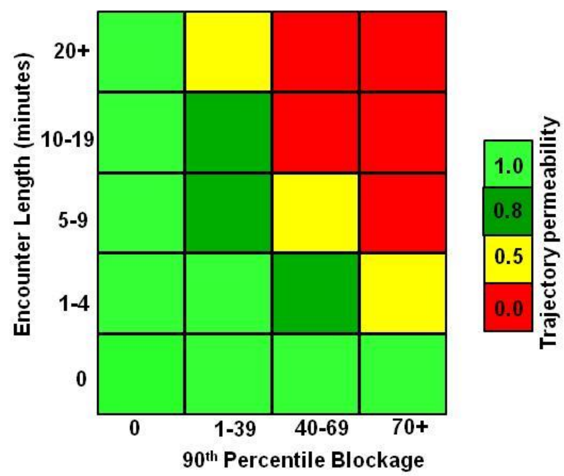

Figure 4. Trajectory impact model used in the airspace classification.

3. EXPANDED MODEL VALIDATION

In an effort to address these validation shortcomings and to improve our insight into the relationship between permeability and the achievable, sustainable capacity that is required for strategic planning, our research efforts this past year have focused on three primary areas: improving the validation methodology, expanding the data set of weather impacted days, and examining additional regions of the NAS that have different demand profiles, ATC operational priorities and weather characteristics.

2014 Weather Impact Days

During the summer of 2014, data were collected and processed on 44 additional weather impacted days. This included days with a wider range of weather characteristics from late Spring synoptic scale storms, to Summer midday convection due to heating, to early Fall storms with weaker convection. One of the days with significant delays was 13 June. A plot of the 15 minute flow rates, the transition time, and the permeability estimate is shown in figure 5.

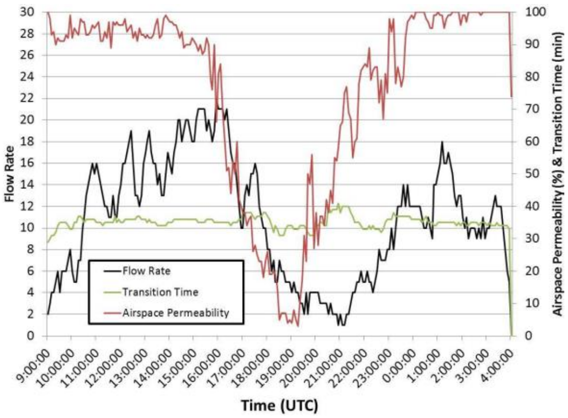

Figure 5. Observed 15 minute flow rate, transition time and airspace permeability estimate for June 13, 2014 for the ZOB/ZNY transition airspace (ZNY001).

On this day, a cold front was oriented north-south across the ZOB/ZNY transition airspace. Two separate lines of convective weather developed over the airspace during the afternoon and then moved eastward towards the NY metro airports. The airspace permeability estimate for this airspace on this day shows excellent agreement with the flow rates as the weather develops, beginning at approximately 16 UTC (noon local time). As the spatial extent and intensity of the weather grows, the observed flow rate and permeability estimate decrease synchronously until 19:30 UTC. As the weather developed the air traffic managers were able to reroute the excess demand north into the Boston ARTCC (ZBW) and south into the Washington DC ARTCC (ZDC) allowing the air traffic to continue to reach the NY metro airports. At 19:30 UTC it is observed that the permeability estimate begins to increase while the flow rate continues to drop reaching a minimum of 2 aircraft per 15 minute period just after 21 UTC. This noticeable discrepancy between the flow rate and permeability is explained through an analysis of the weather images and the ATCSCC program logs. As the weather moves eastward, it exits the ZOB/ZNY transition airspace allowing the permeability estimate to increase. However, the weather then begins to impact the NY metro airports. The weather impact at the airports is significant enough to shut down all flow into the NY Terminal Radar Approach Control (TRACON). With the downstream resources significantly impacted, the flow through ZOB/ZNY cannot resume until the weather clears the airports. With such significant impacts at the NY metro airports, the air traffic managers issued Ground Stop programs, in essence grounding all flights heading into NY and decreasing future demand into the airspace.

A statistical validation of the impact model was performed for the ZOB/ZNY transition airspace using data from the original 2013 case days and the 44 additional days from 2014. The data set was filtered to only include hours between 18 UTC and 00 UTC when the airspace experiences the highest demand. Figure 6 is a box and whisker plot of the permeability estimates binned into increments of 20%. A correlation between the airspace impact model and the flow rate is clearly visible. As the convective weather impact increases (measured by a decreasing permeability), the flow rate decreases accordingly.

Using the mapping of permeability to flow rate provided in figure 6 (i.e. median flow, 75 percentile and maximum observed flow) planners could create traffic management programs that are tailored for the specific scenario of the day. For instance, for short-lived events, air traffic planners may chose to set flow rates near the maximum achievable rate for the permeability estimate forecasted. In this instance, planners may feel confident in the ability to push the workload of the air traffic controllers and sustain high flow rates due to the limited impact duration of the event. On another day, a planner may predict that the convective weather will be long-lived and that it will not be possible to set higher rates due to the difficultly in sustaining a high workload for a long period of time. In this scenario, planners may chose to set rates closer to the median flow rates observed for this airspace.

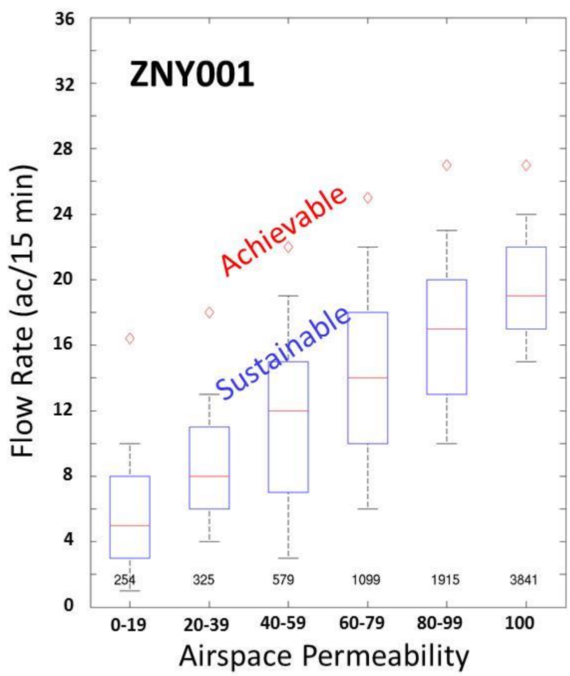

Figure 6. Box and whisker plot of the observed 15 minute flow rate for the ZOB/ZNY transition airspace (ZNY001) binned by airspace permeability estimates. The red dash is the median flow rate, and the box represents the 25th and 75th percentile values. The maximum observed flow rate for each box is also shown in a red diamond. The count of observations used in each bin is shown at the bottom of the plot. Data is for 85 case days from the summer of 2013 and 2014.

3.1 Expanded resource data set

Two additional airspace regions were analyzed to determine the feasibility of the model in airspace regions that may not experience demand as high as the NY region or may have more flexibility in tactical rerouting. The first airspace analyzed (ZDC002) is a region where aircraft are flowing north-south along the southern portion of the east coast over North Carolina. This airspace is a region where aircraft transition between the Jacksonville ARTCC (ZJX) and the Washington DC ARTCC (ZDC). Depending upon the offshore military constraints, this airspace has flexibility in aircraft deviations due to weather and does not regularly experience its maximum potential flow rates. Figure 7 depicts the airspace crossing line and the typical flows through the ZJX/ZDC transition airspace.

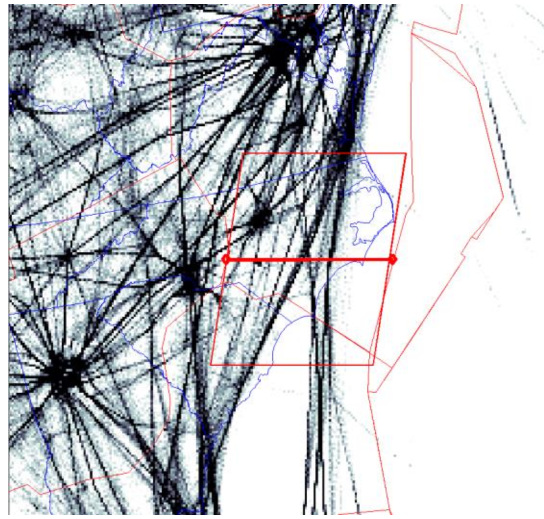

Figure 7. Orientation of the ZDC002 airspace crossing relative to the ARTCC boundaries and common route structures. This airspace is a transition region between the ZJX and ZDC ARTCCs.

A statistical validation of the impact model is shown in figure 8 for the ZJX/ZDC transition airspace. The data set is also filtered to only include data between 18 UTC and 00 UTC when the airspace experiences the highest demand. The permeability estimates are binned in increments of 10 percent for greater fidelity. The correlation between the flow rate and impact model is not as clearly defined as for the ZNY001 airspace. Observed flow rates increase with permeability, as the permeability increases from 20% to 70%. However, for permeability greater than or equal to 70%, the curve begins to flatten. We hypothesize that this flattening of the curve is due to the fact that the fair weather capacity of the airspace exceeds the current demand and that there is sufficient residual capacity to handle demand even with some weather impacts. More data are needed at the low end of the permeability range to validate the calibration for extremely high impacts.

The second airspace analyzed (ZOB005) is a region where aircraft are flowing east-west over eastern Ohio. This airspace is a region where aircraft are controlled entirely by ZOB. This airspace is west of the ZNY001 airspace previously analyzed and controls a significant amount of the volume of aircraft flowing to/from the NY metro airports. The airspace is also less constrained that ZNY001, as controllers have more flexibility to vector aircraft around storms before they ‘lock into’ their transition trajectories in ZNY airspace. Figure 9 depicts the airspace crossing line and the typical flows through the ZOB.

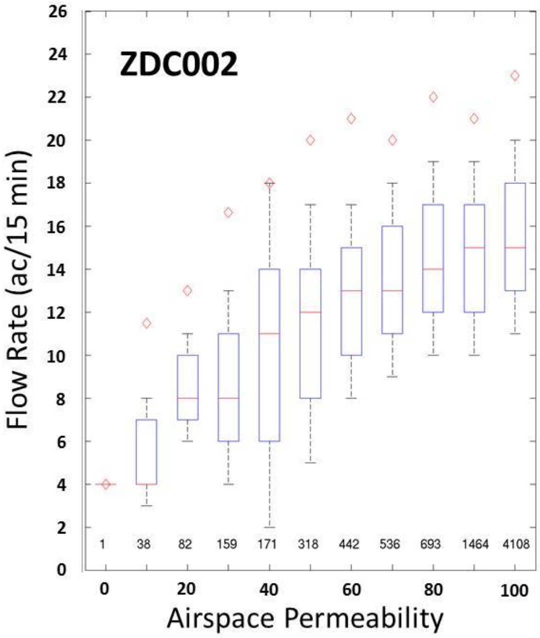

Figure 8. Box and whisker plot of the observed 15 minute flow rate for the ZDC/ZJX transition airspace (ZDC002) binned by airspace permeability estimates. The red dash is the median flow rate, and the box represents the 25th and 75th percentile values. The count of observations used in each bin is shown at the bottom of the plot. Data is for 85 case days from the summer of 2013 and 2014.

A statistical validation of the impact model is shown in figure 10 for the ZOB east-west flows (ZOB005). The data set is also filtered to between 18 UTC and 00 UTC and binned in increments of 10 percent. The correlation between the flow rate and impact model is visible but noisier than observed for ZNY001, particularly the observed maxima. An analysis of these 'high maximum' events show that ZOB was accepting aircraft that were diverted out of the southern routes through the Indianapolis ARTCC (ZID) due to significant weather impact there. During these events the increased flow rates were sustained only for short periods of time, suggesting again the importance of understanding the difference between achievable and sustainable flow rates during times of weather impact.

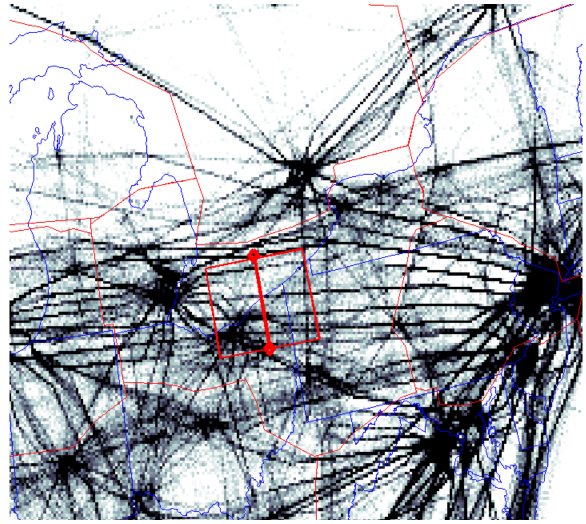

Figure 9. Orientation of the ZOB005 airspace crossing relative to the ARTCC boundaries and common route structures. This airspace covers the primary east-west routes through the Cleveland ARTCC.

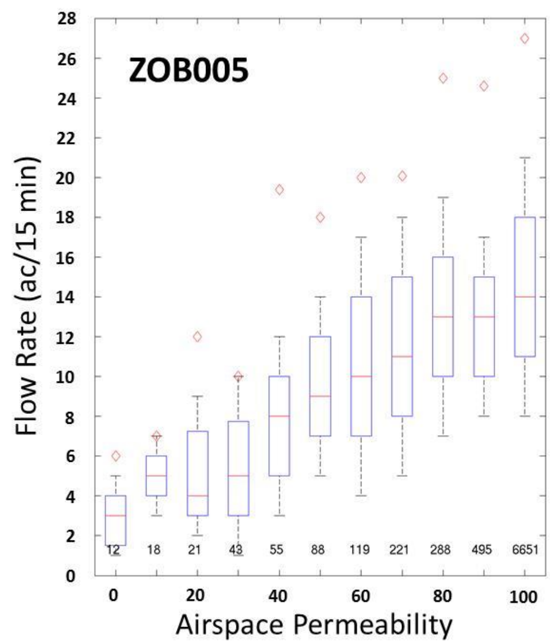

Figure 10. Box and whisker plot of the observed 15 minute flow rate for the ZOB east-west flows (ZDC002) binned by airspace permeability estimates. The red dash is the median flow rate, and the box represents the 25th and 75th percentile values. The count of observations used in each bin is shown at the bottom of the plot. Data is for 85 case days from the summer of 2013 and 2014.

3.2 Time-lagged validation

As suggested in Section II, a higher than preferred observed flow rate may occur through heavily impacted airspace if creative but difficult to sustain tactical operations are undertaken by air traffic controllers to reduce a large inventory of airborne aircraft. For our validation results this can and does lead to larger uncertainty bounds in the correlation of flow rates and airspace permeability. An example of one such case is September 11, 2013.

Figure 11 plots the 15 minute flow rates, the transition time, and the permeability estimate for September 11, 2013. At 17:30 UTC the permeability estimate rapidly decreases as the weather develops, dropping below 40% at 18 UTC. Due to the lack of a strategic plan on this day, air traffic managers are forced to deal with this excess demand on a severely constrained resource and continue to push aircraft through highly impacted airspace. Figure 12a depicts the strong convective weather that has developed at 18:45 UTC and the high volume of departure and arrival streams sharing the same airspace. The aircraft transition time also increases from the nominal value of 34 minutes to approximately 60 minutes during the peak of the weather event as traffic is vectored around storms.

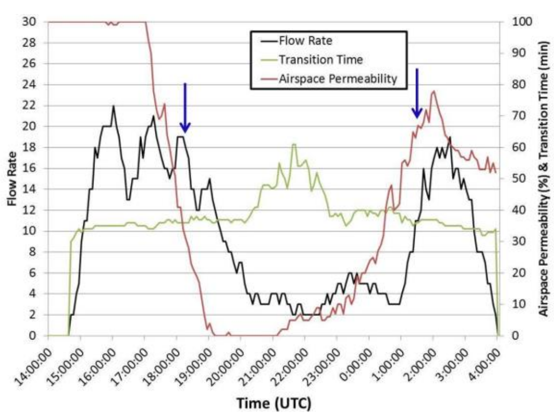

Figure 11. Observed 15 minute flow rate, transition time and airspace permeability estimate for September 11, 2013 for the ZOB/ZNY transition airspace (ZNY001). The blue arrows denote instances the permeability estimate and flow rate disagreed due to poor strategic planning.

It is also important to note that as the weather event ends at 00 UTC, the flow rate does increase; however, the flow rate lags the increase in permeability by one hour, leaving unused capacity that is badly needed to begin recovery from the day's impacts. Figure 12b depicts the airspace at 01 UTC when the demand is near zero as the air traffic managers prevented aircraft from departing for this airspace during the time of impact.

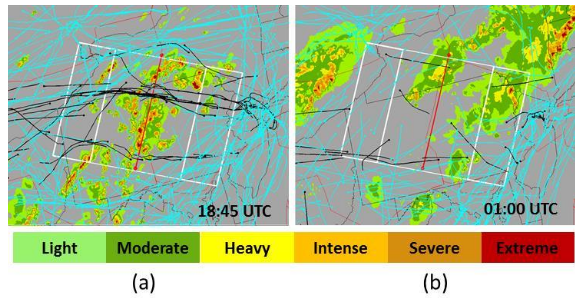

Figure 12. Aircraft trajectories on September 11, 2013 at 18:45UTC (a) and September 12, 2013 at 01:00UTC (b) traversing the ZOB/ZNY transition airspace (ZNY001) and observed precipitation intensity. The trajectories in black are associated with the ZNY001 resource. The trajectories in cyan are not associated with the airspace.

To this point, the validation methodology has assumed that the weather in the airspace is impacting the flow rates of the aircraft currently in the airspace. However, during times of storm initiation or dissipation with poor strategic planning, this assumption has been shown to be incorrect. To account for this we modified the validation methodology to perform a time-lagged validation. To do this, we simply used the flow rate observed 60 minutes after the permeability estimate. The initial validation showed a poorer correlation for the ZDC002 airspace when the permeability estimate was below 50%. Figure 13 is a revised statistical validation for this same data set using the time-lagged validation methodology. A much clearer correlation can be observed between the time-lagged flow rates and the airspace permeability. Further analysis is needed to correlate validation with traffic management decisions to determine when it is appropriate to correct for time lags observed in the response of traffic throughput to permeability changes.

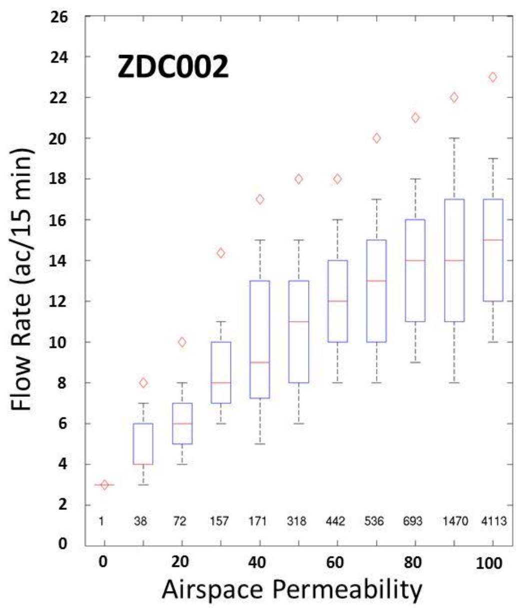

Figure 13. Box and whisker plot of the 15 minute flow rate observed 60 minutes after the permeability estimate for the ZDC/ZJX transition airspace (ZDC002) binned by airspace permeability estimates. The red dash is the median flow rate, and the box represents the 25^{th} and 75^{th} percentile values. The count of observations used in each bin is shown at the bottom of the plot. Data is for 85 case days from the summer of 2013 and 2014.

4. OPERATIONAL FIELD EVALUATIONS

In the summers of 2014 and 2015, MIT Lincoln Laboratory performed field assessments of the operational usage of the CoSPA 2 to 8 hour aviation weather forecast. Lincoln Laboratory staff regularly visit the real-time operational facilities to evaluate the capabilities of the aviation weather products provided to users during the convective weather season. During the summer of 2014 the observation team gathered data from three separate convective events covering four days (24-25 June, 14 July, and 12 August). The team visited four ARTCCs and the ATCSCC, in addition to two commercial airlines. During the summer of 2015 the observation team again conducted observations and gathered data from three separate convective events covering four days (13-14 July, 3 August and 20 August).

During the observations at the ATCSCC, the traffic planners repeatedly discussed with the observation team the need for assessing decision risk in the deterministic CoSPA forecast and applying that directly to ATC impact. This provided a unique opportunity to discuss the airspace impact translation model with operational planners and provide example forecasts based upon the model in a pseudo-real-time environment. During the 24-25 June 2014 observational blitz, planners consulted forecast permeability plots from CoSPA provided by Lincoln personnel to learn about and assess the performance of the product. Similar plots were provided to ATCSCC planners on 25 June 2014 as severe weather continued to march across the east coast. Planners once again consulted and continued their assessment of the new product. All user comments, questions, and suggestions from the planners on these two observation days were used in the development of web-based display concepts for an application based upon the translation model.

On 14 July 2014 the CoSPA observation team returned to the ATCSCC in anticipation of a highly convective day that had the potential to impact operations in the NY metro region. The Air Traffic Management (ATM) planners were shown a prototype display of the CoSPA forecast product translated into operational impacts. An example is provided in figure 14; the display resembles a combination of both CoSPA and the Route Availability Planning Tool (RAPT) [10]. Note that the operational display concept labeled the permeability estimate as the 'Forecasted Flow Constrained Area (FCA) Blockage' percentage on the left-axis and also displayed hourly flow rates assuming a one-to-one correlation between permeability and flow on the right-axis.

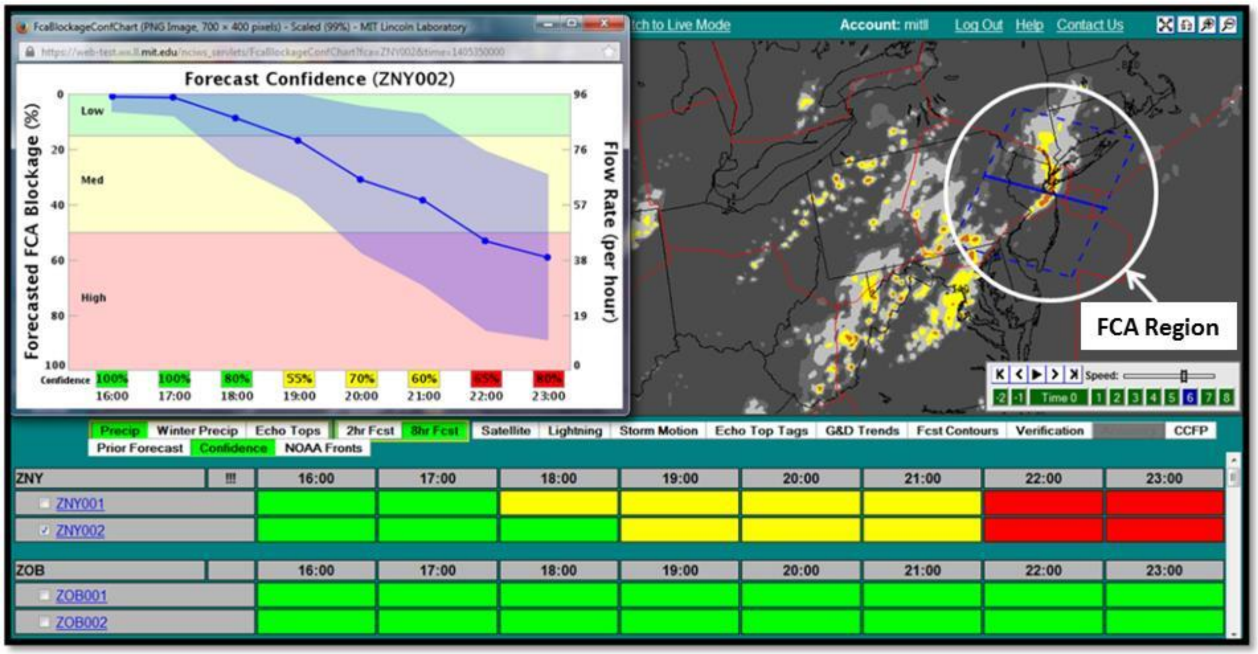

Figure 14. Example of the prototype display of permeability estimates at 1500 UTC on 14 July 2014.

The severe weather planner and National Operations Managers (NOM) on duty that day were highly experienced and were already modeling TMIs in preparation for severe weather impacts in the NY region. During the course of the morning strategic planning time period, ATCSCC planners asked to see the modeled impacts four times as verification of the AFP rates they were modeling for the day. One planner stated, “I like the new flow rate addition and am very pleased with the web interface”.

On the final CoSPA operational evaluations for the summer of 2014 on 12 August, the ATCSCC personnel were provided with web access to the translation tool. During the course of this day severe weather plans and the NOM viewed the website seven times during the strategic planning process. Prior to the first Strategic Planning Teleconference (SPT) with the ATC facilities and the stakeholders the planners viewed the forecast translation product and incorporated the information into the collaborative planning process.

Strategic planning on 12 August 2014 proved to be a unique challenger for the planners. Following the initial weather briefing and with guidance from the translated forecast product estimate of flow reduction, ATCSCC personnel determined that AFPs would be required in the NY/DC region as well as in northern Florida. Typically, when convective weather is expected to constrain airspace in the NY/DC region two AFPs are issued. One AFP is placed in response to the forecasted convective constraint while the second is used to control the extra demand as a result of rerouting. However, a review of the translation product from CoSPA indicated that storms would limit the flow in several of the NY/DC corridors but also in Florida and thus required a third AFP in ZJX. Planners also were concerned that AFPs cannot be active in both ZJX and ZDC at the same time due to a delay-compounding effect on flights traveling in the north-south corridor of the east coast. The corridor between these two regions is heavily traveled by shuttle services that carry aircraft on similar routes several times a day. Therefore, with both AFPs in place at the same time, aircraft traveling from the Northeast to Florida would incur a delay heading south through ZJX, and then additional delay heading north through ZDC. Thus, ATCSCC planners needed to determine if the ZJX AFP could be terminated before beginning the ZDC AFP.

Discussions on timing and flow rates were well underway immediately following the first SPT at 1115 UTC. At 1230 UTC, planners viewed the resource constraint predictions of the ZNY, ZDC, and ZJX regions. Comparisons between predicted flow rates and the CoSPA deterministic placement of storm cells were discussed for the next thirty minutes. The planners eventually based their decision upon the flow rate predictions from the translated products, deciding that the intensity and timing of these two weather impacted regions would require an AFP in northern Florida and two AFPs in the NY/DC airspace. The ZJX AFP would begin at 1300 UTC and last until one minute prior to 1800 UTC. The final two AFPs over the DC and NY airspace would begin at 1800 UTC, immediately after the AFP ended over ZJX. The planner most directly involved with the strategic planning on this day commented that the translated forecast product was an important part of the strategic planning and was a great asset in the planning of the timing of the event as well as the rates to set for each of the AFPs.

The summer of 2015 observations mirrored many of the same conclusions from the 2014 operational blitz periods. Planners consulted the translation tool via the web to assess the impact of the convective weather on the traffic flows from the strategic 2-8 hour forecasts. A full report of the summer 2015 observations is being prepared and will be available at a later time.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This paper has presented the results of research to predict the impact of convective weather on operations using a flow-based permeability measure. The results have shown good agreement between the permeability estimate and measured flow rates for a major air traffic resource controlling flow east/west bound for the NY metro airports. The permeability estimate forms the basis for a weather impact assessment that air traffic planners could use to anticipate the constraints on the air traffic control system and set rates as well as start times of traffic management initiates.

By translating convective weather forecast information into the parameters used in selecting TMIs (e.g., time of onset, level of impact [permeability and flow rates], and duration), it is hypothesized that more effective and timely TMIs can be formulated and assessed in operations. Additionally, we believe that communicating forecast uncertainty as expressed using those same decision variables provides an objective, quantitative basis to better understand and communicate the risks and benefits of various levels of TMI strategies. However, more research and evaluation is needed to verify these hypotheses and ensure that decision support information meets user needs.

This paper also extended the validation of the permeability estimates in regions of the NAS that do not experience the high-volume demand of the region immediately around the NY metro airports. Both of the regions demonstrated a correlation between the permeability estimate and the flow rates, however, each demonstrated different characteristics of the airspace in the analysis. For the first airspace, over coastal North Carolina, the results reflected the fact that this airspace does not experience its maximum potential capacity during times of clear weather. Therefore, during times of weather impact, the nominal flows rates are able to be managed until the permeability estimate drops below 50%. The second airspace, over central Ohio, demonstrated the ability to handle significantly high flow rates during times of weather impact for short periods of time. Although these flow rates are achievable, they are not sustainable and should not be planned for during times of convective weather. This paper also discussed ways to adjust the comparison of observed traffic and predicted impacts that account for operational decisions that may decouple the observed traffic flow from weather impacts in the local airspace. Finally, operational experience with an early decision support prototype based on the proposed impact model was described.

Future model development should continue to validate the permeability estimates for a wide range of strategic flows through airspace resources with different configurations, traffic demands, and weather scenarios. The validation methodology should also look at ways to measure and account for times where high flow rates are maintained at the expense of higher controller workload. This will be important to answer the question of whether the weather impact was managed through reduced flow rates or higher workload. In the future, given objective forecasts from strategic weather forecast products such as CoSPA or SREF and a translation model, as described in this paper, it would be possible to develop disciplined TMI decision making methodologies to manage an appropriate flow rate while not overtaxing the air traffic control personnel.

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