3.3 MEASURING THE UTILIZATION OF AVAILABLE AVIATION SYSTEM CAPACITY IN CONVECTIVE WEATHER[†]

Michael Robinson*
William Moser
James E. Evans
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02420-9185

1. INTRODUCTION

The U.S. National Airspace System (NAS) operates as a complex air traffic network comprised of airport terminal nodes connected by multiple en route airway paths. The most severe disruptions to NAS network operations are caused by summertime thunderstorms, which decrease available en route and/or terminal airspace capacity. This can result in large delays, diverted airborne flights, and flight cancellations.

There is currently great interest in improving the ability to quantitatively assess how well U.S. Air Traffic Management (ATM) services are provided, particularly as new weather-ATM decision support capabilities are made available. The RTCA/S2K FAA/airline Customer Perspective Metrics Working Group (CMWG) (Boone et al. 2006) has been studying how to more accurately measure the performance of the air traffic system. One of the three primary areas for assessment identified by the CMWG[1] is resource utilization, which they defined as "the safe and efficient use of available airport or airspace capacity." To date, the CMWG has not developed a quantitative metric for measuring resource utilization.

Measurement of capacity utilization during convective weather is difficult because storms cause capacity reductions in both en route and terminal airspace regions. In particular, en route capacity loss results in network congestion that cannot be readily characterized by scalar metrics such as the ratio of overall demand to a single capacity number.

To assess how effectively the available capacity had been utilized, this paper proposes to estimate the optimal capabilities for airspace usage during convective weather. This is accomplished with the following two-step modeling approach:

(i) translate three-dimensional weather radar data and other germane capacity impact weather data (e.g., terminal ceiling and visibility, terminal surface winds) into time-varying estimates of the capacity reductions in affected airspace regions
(ii) automatically generate an objective, broad-area ATM strategy that considers the time-varying estimates of airspace capacity and the demand to determine optimal reroute strategies (and when necessary, minimally disruptive ground or airborne delay initiatives[2]).

By comparing the actual airspace capacity usage with the model solution for the most feasible use of available capacity, one can objectively assess the effectiveness of operational ATM during convective weather impacts. These comparisons provide estimates of avoidable and unavoidable delay of the NAS network, which can be reevaluated with altered network states (e.g., increased demand, changes in capacity, alternative decisions) to quantify resultant changes in ATM performance..

The results of the actual vs. modeled comparisons of capacity usage can support a number of weather-ATM related NAS investment and performance assessment issues:

- Quantitative estimates for "resource utilization" metric
- Business-case development for new weather-ATM decision support capabilities

---

[†] This work was sponsored by the National Aeronautics and Space Administration (NASA) under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

*C*orresponding author address*: Michael Robinson, MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9108; e-mail: miker@ll.mit.edu

[1] The other two key areas identified by the CMWG are "predictability" and "coordination"

[2] The approach outlined here is closely related to a major FAA traffic flow management (TFM) capability identified for TFM modernization: automated airspace congestion management (AACM) including airspace congestion resolution. The approach outlined here can be viewed as AACM with perfect weather forecasts.

- Next-day FAA/airline review and post-event assessment of implemented tactical/strategic weather-ATM decisions
- Quantitative studies of the network usage changes that would occur with proposed NAS capacity enhancements (e.g., airway modifications, new runways, etc.)
- Improved measurement of ATM performance and greater airline/public awareness of unavoidable delay
- Resource utilization ramifications of fleet mix changes or changes in air traffic demand
- Improved traffic manager training that includes studies of actual "missed opportunity" scenarios identified in the comparisons

A description of Weather-ATM Capacity Utilization (WACU) model is presented in Section 2. Case study applications of the model are presented in Section 3. In this Section, comparisons of air traffic delay statistics for actual vs. good-feasible weather-ATM strategies are shown for three convective weather impact events in 2005 and 2006. Air traffic "flow-specific" capacity-usage comparisons during these events are also presented to demonstrate how the use of this model may help identify opportunities for improved tactical ATM during convective weather.

Discussions of additional applications for the Weather-ATM capacity model (noted briefly above) are presented in Section 4. Finally, opportunities to improve the model and provide more robust estimates for unavoidable delay are summarized.

2. WEATHER-ATM CAPACITY UTILIZATION (WACU) MODEL

An integer programming (IP) model developed by Bertsimas and Stock-Patterson, (1998) was adopted to determine automated, broad-area ATM strategies consistent with time varying reductions in airspace capacity caused by thunderstorms. In the model, the NAS is characterized as a set of airports interconnected via en route sectors. Each airport and en route sector is assigned time varying aircraft capacities. Individual flights are modeled as traversals of sectors forming paths between pairs of origin and destination airports (Figure 1). The model accounts for aircraft speed and altitude by specifying the valid paths and minimum sector traversal times The model solution yields the minimal cost (in terms of airborne and ground delays) and the flight plan for each flight -- takeoff and landing times, and arrival times at each sector along its path. Using 1990s state-of-the-art IP solvers and hardware, Bertsimas and Stock-Patterson, (1998) showed that ATM problems of significant size (six major airports, with three thousand flights over a sixteen-hour period) could be solved optimally using only a few minutes of computation time.

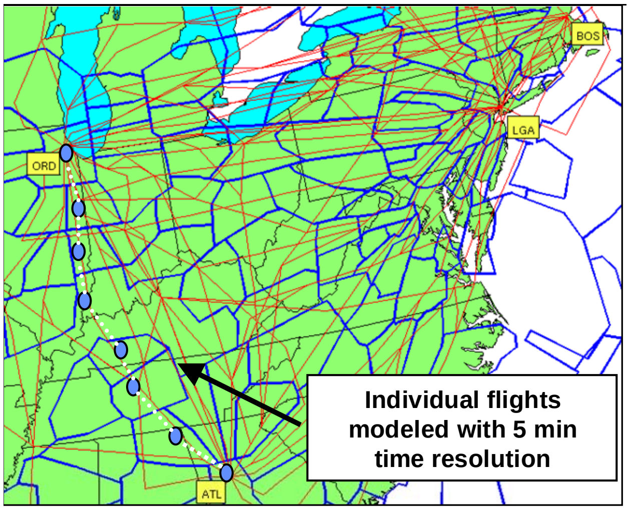


Figure 1. Individual flights in the WX-ATM Capacity Utilization (WACU) model are represented as traversals of sectors forming paths between pairs of origin and destination airport. Blue lines mark sector boundaries and red lines are standard jetways. This example shows the path of an individual flight, modeled with sector traversals, from Atlanta airport (ATL) to Chicago O'Hare (ORD) airport.

The FAA Aviation System Performance Metrics (ASPM) air traffic schedule database is used as the basis for the "ATM problem" for a given day. The ASPM schedule provides the nominal departure and arrival times for commercial aircraft flying into or out of the largest seventy-five airports in the U.S. For the studies described here, we were primarily interested in convective weather impacts and weather-ATM solutions in the highly congested northeast NAS quadrant. Therefore, the model domain was the airspace region covering the Northeast and Mid-Atlantic regions of the country. Other regions of the country were modeled as having essentially infinite capacity. With this restriction, and considering only commercial air traffic, we consider between ten and twenty thousand aircraft for a particular model run.

An optimized traffic assignment to the NAS network is generated by an Integer Programming (IP) algorithm with binary decision variables representing traversals of airspace sectors by aircraft at five minute intervals. Each flight is assigned a set of potential paths – sequences of sectors – it may traverse to get from origin to destination. These paths are derived from the FAA preferred route and coded departure route databases, with additional "straight-shot" paths added between city pairs for which no route information exists in the databases. Since the decision variables model airspace traversals at the sector level, which sectors an aircraft traverses on a particular route, along with its nominal sector traversal times, are determined. A simple flight elevation profile was assumed for all aircraft, with a constant ground speed of 450 knots. These flight path data were used to map routes to sectors and to compute minimal (per-aircraft) sector traversal times. The model allows some deviation from the nominal traversal times: "holding" in a particular sector is allowed, as well as early arrival, within parameterized limits. We use aggregate runway departure and arrival rates to meter flights into and out of an airport. Other terminal airspace flight details (e.g., handoffs between various controllers) were not modeled in the cases reported here.

The IP formulation of the ATM traffic assignment problem by Bertsimas and Stock-Patterson, (1998) minimizes a notion of overall delay in the system subject to a variety of constraints on flight movement (i.e. on the decision variables). The constraints can be grouped into a number of families:

- Path-defining constraints
- Decision variable semantics
- Flight consistency constraints
- Airspace capacity constraints

The first two families simply define the network-like view of the NAS, with network "nodes" representing NAS sectors. The third family models the notion of a flight's traversal of the NAS between two points as a path in the network -- a sequence of contiguous sectors between the origin and destination. The last constraint family ensures that modeled aircraft operations in the network adhere to sector capacities and airport arrival and departure rates.

To account for the impacts of convective weather on sector capacities – and to translate weather radar information into statements of airspace sector availability - reductions in available airspace capacity are estimated by a Weather Sector-Route Blockage (Wx-RB) model developed by Martin et al. (2006). The Wx-RB model statistically computes the fraction of routes in a sector that are blocked (and thus the fractional sector capacity loss) by strong, high-topped thunderstorms (see Figure 2, from Martin et al. 2006). Precipitation and Echo Tops products from the Corridor Integrated Weather System (CIWS) were used as weather input into the Wx-RB model. The blockage fractions are used to downward-adjust sector capacities at each time step from the nominal FAA Enhanced Traffic Management System (ETMS) Monitor Alert Parameter (MAP) values.

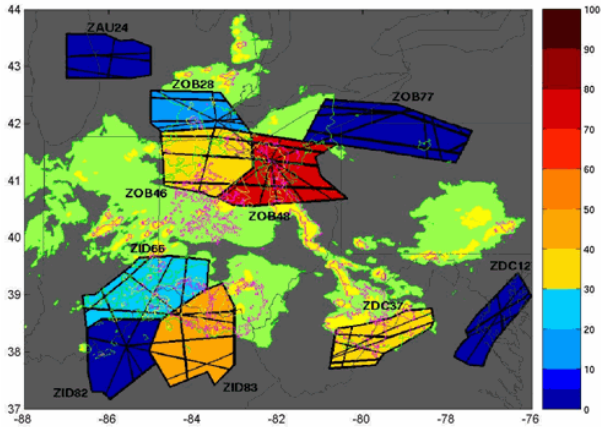


Figure 2. Example of Wx-RB during a significant weather event for some select en route airspace sectors (principal routes through those sectors are shown as black lines). Sectors are colored based on blockage percentage as indicated by the color bar to the far right – dark red is 100% sector-route blockage. Weather depicted in yellow represents precipitation of at least VIP level 3. Magenta contours bound storm echo top heights of at least 32 kft (from Martin et al. 2006).

Model runs are parameterized to include all commercial flights into or out of a user-specified set of airports. The amount of allowable per-flight air and ground delay is also user-specified, as is the scenario duration. Generally, model runs were computed for "day-long" scenarios (288 time steps) and included air traffic for the forty busiest airports in the Northeast NAS quadrant. The allowed total air delay was one hour, with maximum per-sector air delay of 30 minutes. A two-hour window was allowed for departure traffic.

A commercial Linear Programming solver, ILOG CPLEX 9.1, was used to find solutions to the modeled weather-ATM problems. With the parameterizations described above, the resulting ATM problems were large – constraint matrices had over two million columns and five million rows. The problems were too large, in fact, to be solved to optimality, as posed, in a reasonable amount of time (runs could take many days without converging). Two techniques were developed to overcome this difficulty. The first was to develop a two-stage solution algorithm which allowed the model to solve first for a set of “easy” flights, and then to extend this solution to include all flights. The second was to convert the problem from an optimality problem into a feasibility problem. In experiments involving small problems, we saw that, in running to optimality, the solver was able to get close to an optimal solution – one which minimized total delay – relatively quickly. The solver would then spend the bulk of its time finding the optimal solution and proving its optimality.

Generally, a good feasible solution – one within ten or fifteen percent of the optimum – was discovered by the solver within minutes on problems that took hours to run to optimality. We used this observation to modify the model to terminate at a feasible solution which met a user-specified bound for maximum allowable delay. In addition, we extended the model to allow for flight cancellations, and again allowed the user to specify an allowed upper bound for this. In two of the large weather-ATM impact events we modeled (16 and 27 July 2005) we specified delay and cancellation bounds at roughly 10% of that obtained from ASPM data for those days. In attempts to model the 27 July 2006 weather-ATM impact event, the solver could not find any feasible solutions at these bounds. Increasing the bounds to 30% and 50% of actual delay and cancellations, respectively, resulted in feasible solutions and acceptable solution times for the 2006 case event. Since no large cases were run to optimality, we cannot be sure that the cost of the any of the feasible solutions obtained in this manner was “close” to optimal. However, the techniques do provide good upper bounds for unavoidable delay, along with detailed flight plans which can be analyzed to provide insight into how to route flights in order to substantially reduce NAS delays, particularly on the ground.

3. ACTUAL VS. MODELED AIRSPACE CAPACITY USAGE DURING CONVECTIVE WEATHER

The WACU model was applied to the following three convective weather impact events in 2005 and 2006:

1. **16 July 2005:** Widespread outbreak of air mass thunderstorms from eastern Lake Michigan to the East Coast
2. **27 July 2005:** Large thunderstorm squall line from New England to Northern Alabama
3. **27 July 2006**: Widespread, severe, quasi-organized convection in northeast NAS quadrant, with strong thunderstorms directly impacting Chicago and New York terminals

Examples of the convective weather at peak severity on each of these days are shown in Figure 3. These case days were chosen to study model results and comparisons to actual weather-ATM performance for different types of convective weather regimes (air mass storms vs. squall lines), for varying NAS network demand[3], and on days when air traffic delays caused by convective weather were severe[4].

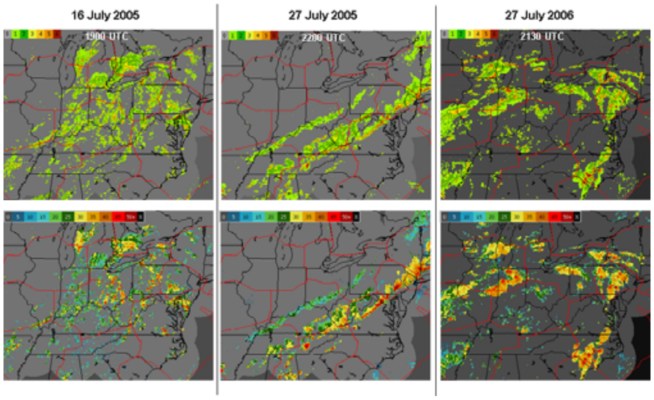


Figure 3. The three convective weather events for which the Weather-ATM Capacity Utilization model was applied. CIWS VIL precipitation is on the top and CIWS Echo Top heights (in kft) are on the bottom.

---

[3] The 16 July 2005 event occurred on a Saturday, typically the day of the week with the lowest air traffic demand.

[4] More flights were delayed on 27 July 2006 than on any other day that year.

Table 1. Actual vs. WACU Model Estimates of Delays and Cancellations Caused by Thunderstorms

		Total Flights	# Flights Delayed > 15 min	% Flights Delayed > 15 min	Average Delay per Delayed Flight (minutes)			Total Delay (hours)	Cancelled Flights
					Ground	Air	Total		
16-Jul-05 0000-2359 UTC	Actual	13340	4325	32%	60.0	-0.7	59.3	4274.5	750
	Model	13340	539	4%	79.6	-4.9	74.8	672.0	75
27-Jul-05 0000-2359 UTC	Actual	14483	4747	33%	60.0	-7.6	51.8	4098.2	559
	Model	14483	465	3%	78.4	-3.3	75.1	582.0	75
27-Jul-06 0000-0359 (28th) UTC	Actual	16328	6623	42%	72.9	-8.5	64.4	7344.8	1136
	Model	16328	896	5%	94.8	-7.4	87.4	1305.2	550

🟩 *WACU estimate of aggregate “unavoidable” delay for each convective weather day*

3.1 Model Assessment of Overall Weather-ATM Performance

Results showing actual vs. WACU model delays on each convective weather day, accumulated from each of the 39 airports included in the model domain[5], are presented in Table 1. Across all three weather days, these results suggest that with perfect knowledge of convective weather coverage and intensity, quantitative information for time-varying airspace capacity loss resulting from this weather, and when using ATM strategies that make the best, feasible use of the available airspace, the number of delayed flights and the total delay could potentially be reduced by 80-90%. In general, the WACU model appears to trade off longer ground delays for a significantly reduced number of cancelled and delayed flights.

The total delay computed by the WACU model is considered the upper-bound measure of unavoidable delay for each weather day (see Table 1, green boxes). On its own, unavoidable delay is a direct measure of the severity of air traffic disruptions caused by thunderstorm activity. Subtracting the model-derived unavoidable delay from the total observed (actual) delay yields the avoidable delay for the convective weather impact period in question.

Avoidable and unavoidable delay statistics can be used for first-order examinations of weather-ATM performance. Tactical and strategic traffic management initiatives, convective weather forecasts, and ATM responses to forecast information can be reevaluated on days with high avoidable delays to determine if alternative strategies may have been more effective. In fact, the impact and effectiveness of alternative weather-ATM approaches can be examined with the WACU model to explicitly measure their effect on NAS network delay. On 16 July 2005 for example, over 4000 flights were delayed 15 min or longer, primarily on the ground as the ATM strategy for managing airspace capacity reductions caused by *en route* air mass convection included eight airport Ground Delay Programs (GDP) and six airport Ground Stops (GS)[6]. WACU model results suggest that more aggressive use of available en route weather gaps (identified via Wx-RB estimates of available sector capacity) was possible, and significantly fewer flights required on-the-ground delays[7].

In this manner of analysis, the WACU model could potentially be used for next-day reviews and testing of alternative weather-ATM strategies.

---

[5] The Capacity Utilization model includes air traffic from the following airports: Atlanta, GA (ATL), Bradley/Windsor Locks, CT (BDL), Bedford (Hanscom AFB), MA (BED), Nashville, TN (BNA), Boston, MA (BOS), Burlington, VT (BTV), Buffalo, NY (BUF), Baltimore, MD (BWI), Cleveland, OH (CLE), Charlotte, NC (CLT), Columbus, OH (CMH), Charleston, WV (CRW), Cincinnati, OH (CVG), Dayton, OH (DAY), Duluth, MN (DLH), Des Moines, IA (DSM), Detroit, MI (DTW), Newark, NJ (EWR), Grand Rapids, MI (GRR), Hartford, CT (HFD), Dulles, VA (IAD), Indianapolis, IN (IND), John F. Kennedy, NY (JFK), LaGuardia, NY (LGA, Little Rock, AR (LIT), Chicago-Midway, IL (MDW), Memphis, TN (MEM), Manchester, NH (MHT), Milwaukee, WI (MKE), Minneapolis, MN (MSP), Chicago-O’Hare, IL (ORD), Philadelphia, PA (PHL), Pittsburgh, PA (PIT), Providence, RI (PVD), Raleigh, NC (RDU), Louisville, KY (SDF), Springfield, MO (SGF), St. Louis, MO (STL), and Teterboro, NJ (TEB).

[6] GDPs for en route convection, typically referred to as “GDPs in support of SWAP” (Severe Weather Avoidance Program), were implemented on 16 July 2005 at BWI, BOS, EWR, JFK, IAD, LGA, ORD, and PHL airports. GS programs for en route convection on 16 July 2005 were implemented at BWI, CVG, EWR, LGA, ORD, and PHL airports.

[7] This is a reasonable assessment given that wholesale en route weather-ATM initiatives are rarely needed during convective weather outbreaks that occur on Saturdays (16 July 2005 was a Saturday) since air traffic demand is typically low on this day of the week.

During the 16 July event, potential alternative strategies may have included removing GDPs from some (or all) of the airports, increasing GDP arrival rates, and/or eliminating airport ground stops for en route convection. Reduced avoidable delay using surrogate weather-ATM strategies implemented in the model would suggest that these alternative ATM approaches may help decrease delay during similar weather impact scenarios in the future.

Computing the ratio of avoidable (A) to unavoidable (U) delay for the three convective weather days in this study provides a comparable measure of ATM performance from one weather impact day to the next (Table 2). Ideally, weather-ATM strategies that result in an A/U ratio equal to zero is desired, meaning that all the delay was unavoidable. A smaller A/U ratio may suggest that, despite larger overall avoidable delay estimates, implemented tactical and/or strategic weather-ATM decisions made better use of available air traffic resources during more extreme weather impacts compared to other days with lower avoidable and unavoidable delays. In terms of the three case studies here, comparisons of A/U ratios suggest that weather-ATM strategies on 27 July 2006 that included the use of Airspace Flow Programs (AFP), coupled with more aggressive use of jet routes in the vicinity of thunderstorms, may have been more effective in mitigating avoidable delay – given the severity of the weather impact event (unavoidable delay) – compared to weather-ATM strategies on 16 July and 27 July 2005, where the overall avoidable delay, but also the severity of the event, were lower. With over 6000 hours of avoidable delay though, WACU model studies suggest that significant weather-ATM improvements were still possible during the 27 July 2006 weather impact event.

Table 2. WACU-Derived Unavoidable vs. Avoidable Delay per Convective Weather Day

	Unavoidable Delay (U) (hours)	Avoidable Delay (A) (hours)	A/U
16 July 2005	672	3603	5.4
27 July 2005	582	3516	6.0
27 July 2006	1305	6040	4.6

3.2 Model Assessment of "Flow-Specific" Traffic Management Initiatives

A key attribute of the WACU model is that the solutions generated can be viewed on a per flight basis and in traffic playback modes (similar to observed traffic flows on ETMS). Hence, the actual weather-ATM decisions pertaining to the usage of specific jet routes, the management of arrivals flows for select airports, tactical reroutes, etc. can be compared to traffic flows derived from modeled weather-ATM strategies to assess the effectiveness of individual traffic management initiatives (TMI). Such comparisons may help air traffic managers to more readily identify missed opportunities to use available airspace capacity and to hone their tactical ATM capabilities.

Presented below are two case study examples from the 27 July 2005 weather event (Figure 4). In each case, WACU model output of flight histories for individual aircraft are compared with actual flight tracks to identify opportunities for improved tactical weather-ATM strategies.

3.2.1 Metro New York / Philadelphia Departure Flow Management

Efficient management of air traffic departing metro New York (NY) airports during convective weather is one of the most challenging ATM tasks in the NAS. The airspace is very complex, the air traffic demand is excessive, and the route structure is rigid and constrained. The resultant high traffic management workload and decision coordination complexity can lead to missed opportunities to increase NY departure route usage efficiency and mitigate delays.

High-fidelity playback capabilities of the WACU model could be used for post-event reviews of TMIs for NY departure traffic. A sample comparison of actual vs. modeled flight tracks for Newark (EWR), LaGuardia (LGA), and John F. Kennedy (JFK) departures on 27 July 2005 is shown in Figure 5. At this time, two primary departure jet routes (J36 and J95) were closed because of convective weather in the vicinity. Key westbound departure routes – J60 and J64 – were also closed at this time (see Figure 5A and 5B). Some excess departure traffic was rerouted to the J80 departure route, but nominal traffic volume and increased routing complexity required spacing restrictions on this route as well. As a result of these route closures and restrictions, a significant number of departing flights were held on the ground at the NY airports and queuing delays quickly mounted.

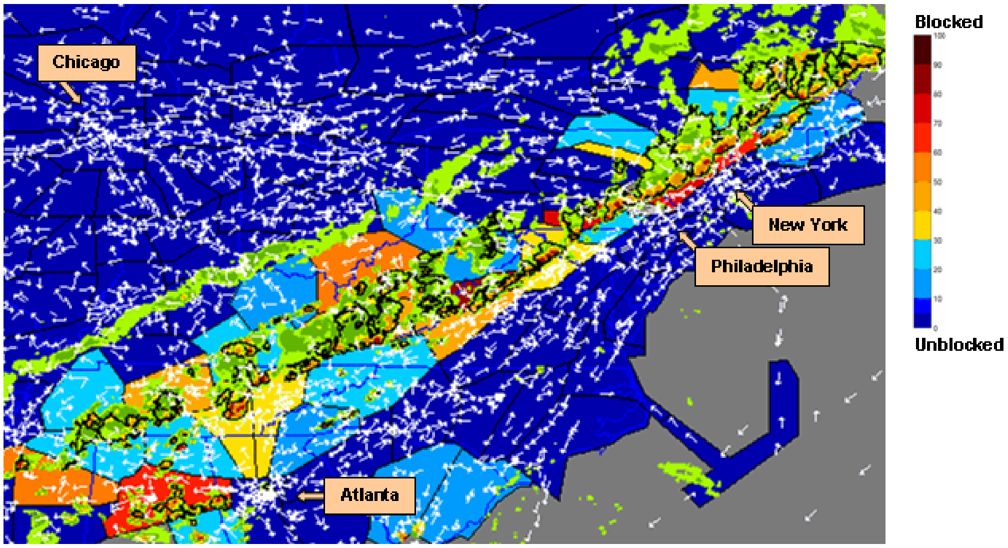


Figure 4. Wx-RB model estimate of available airspace sector capacity reductions caused by a line of thunderstorms at 2130 UTC on 27 July 2005. CIWS 6-level VIL Precipitation depicts weather intensity. The black contour depicts 32 kft+ CIWS Echo Tops. This Wx-RB sector capacity information is ingested by the WACU model to determine good feasible solutions for weather-ATM strategies during this convective weather event.

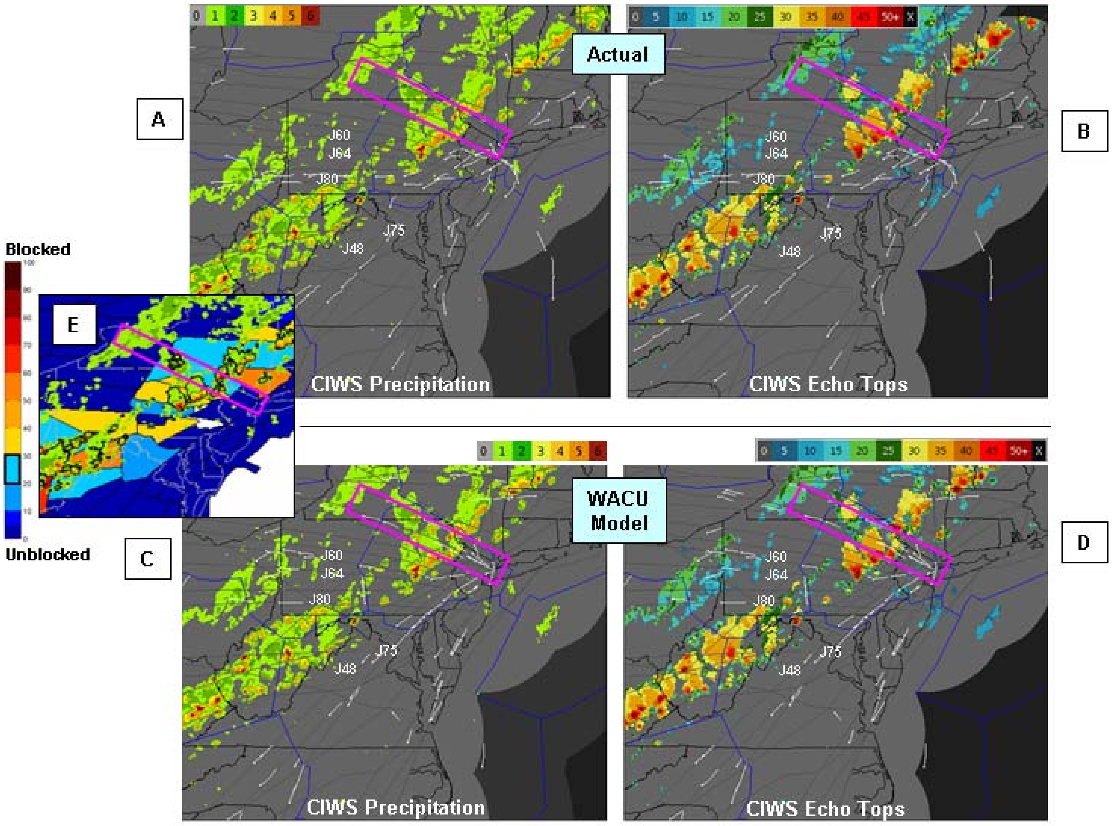


Figure 5. Actual (top – A and B) vs. WACU-modeled (bottom – C and D) metro New York departure traffic (EWR, LGA, JFK airports) at 1945 UTC on 27 July 2005. Actual and modeled flight tracks are overlaid atop CIWS VIL Precipitation and Echo Tops. Available sector capacity at 1930 UTC, derived from the Wx-RB model, is shown in (E). The rectangle in each panel notes the J36, J95 NY departure jet route corridor. Additional departure routes are labeled.

Table 3. Actual vs. Model EWR, LGA, JFK Departure Delays on 27 July 2005.

		Total NY Departure Flights	# NY Departure Flights Delayed > 15 min	% Flights Delayed > 15 min	Average Delay per Delayed NY Departure Flight (minutes)	Total NY Departure Delay (hours)
					Ground	
0000-2359 UTC	Actual	1055	507	48%	73	617
	Model	1055	58	5%	58	56
1900-2000 UTC	Actual	82	58	71%	108	104
	Model	82	8	10%	88	12

The WACU model, noting that there was available sector capacity (see Figure 5E – sectors for J36/J95 only 20-30% blocked by weather), used the J36 and J95 jet routes much more than had been the case during actual events (see Figure 5C and 5D). In addition, with sectors for westbound NY departures only 20-40% blocked by weather, the WACU model merged J60 and J64 departure traffic into one stream (rather than closing both routes) to allow aircraft more space to navigate around a large storm cell near these airways. By using departure airspace that had been closed in real-time so as to reduce demand on alternative departure routes, the WACU model significantly decreased NY departure delays (Table 3).

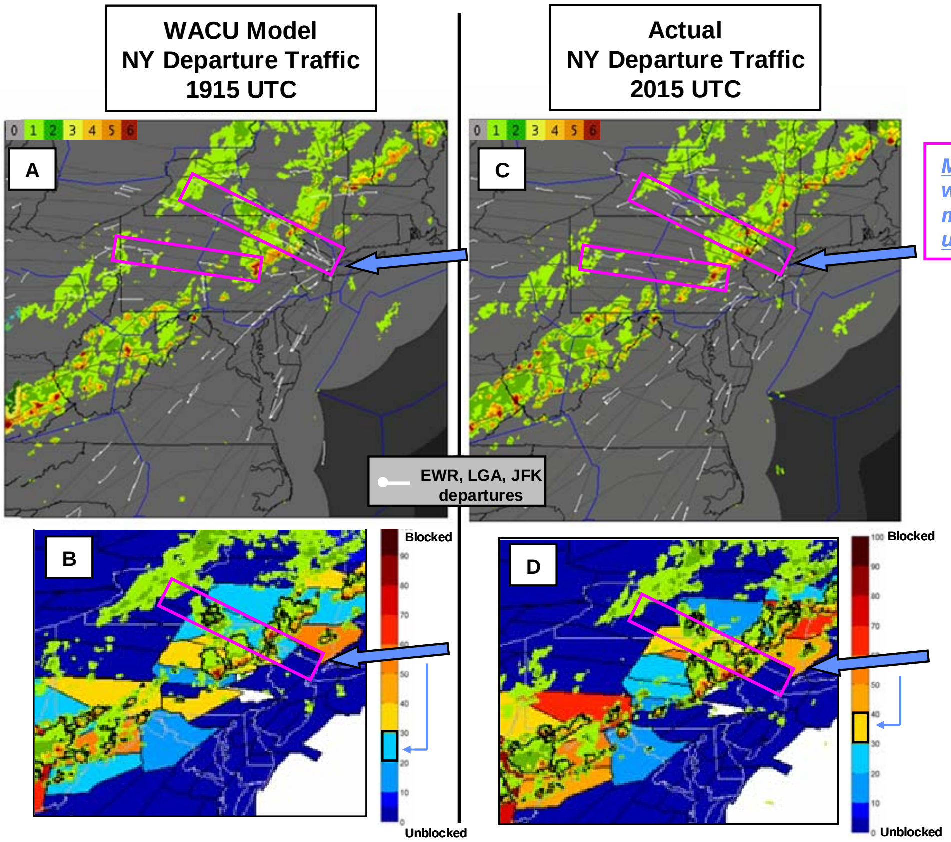
A reasonable question about this comparison is whether the available departure route capacity suggested by the model could have been identified by traffic managers during the actual event. A comparison of actual NY departure routing decisions at 2015 UTC on 27 July 2005 to the model-derived weather-ATM solution at 1945 UTC (30 minutes earlier) show that, in this case, ATC decision-makers would utilize the WACU-modeled tactical strategies under similar (if not worse) weather conditions (Figure 6). During the actual weather impact event, earlier departure restrictions or route closures, and the resulting escalation in delays, made the aggressive use of available J36 and J95 jet route capacity more of a necessity after 2000 UTC.

Departure flow management during convective weather is also a considerable problem for Philadelphia International Airport (PHL). PHL traffic operations are often impacted by en route constraints as the Northeast NAS traffic flow managers seeks to mitigate NY and metro DC traffic impacts (to the north and south of PHL) as well as to equitably manage other northbound / southbound over-flight traffic to Boston and Florida, respectively.

Comparisons of WACU model flight tracks vs. actual flight tracks could also help PHL traffic managers identify missed opportunities for increased weather-ATM efficiency (Figure 7). Flight-by-flight comparisons of actual vs. modeled air traffic flows can be used to better understand the consequences of weather-ATM strategies that do not make most effective use of available NAS network capacity. Figure 8 compares the location of actual EWR, LGA, JFK, and PHL departure flights with the modeled-derived location of these same flights. These results show that the improved use of available airspace capacity allowed:

- More flights to take off and traverse through the Midwest (on nominal departure routes) with less delay [Figure 8, see (1)]
- More flights to more quickly traverse the extended squall line, decreasing flight distances as well as the workload for controllers managing weather impacted sectors [Figure 8, see (2)]
- More flights to avoid reroutes to the south, preventing the needed volume management initiatives that increased delay for actual flights [Figure 8, see (3)].

With flight-by-flight WACU model comparisons, one can explicitly note the network effect of implemented weather-ATM strategies.

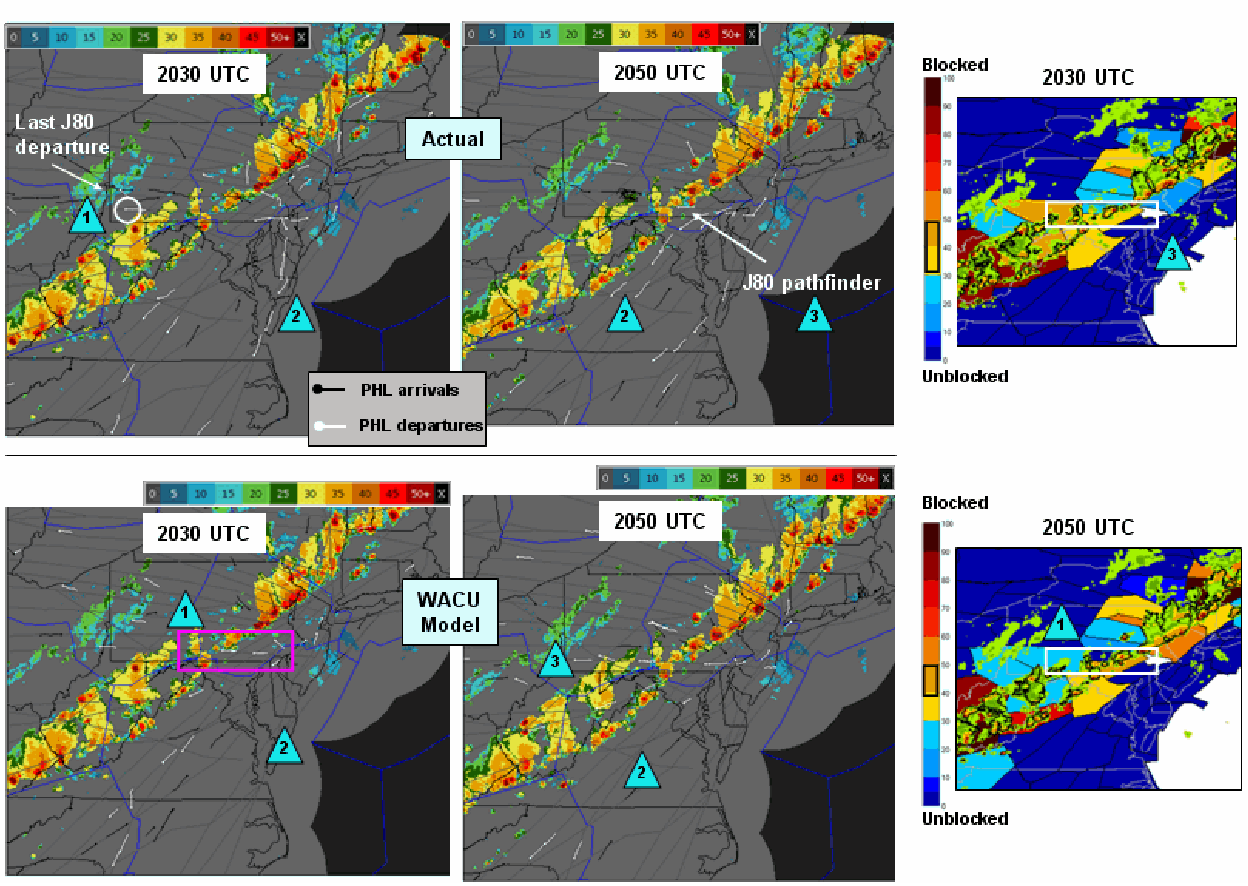

WACU Model NY Departure Traffic 1915 UTC

Actual NY Departure Traffic 2015 UTC

Modeled traffic flow through weather-constrained sectors mirrored by actual route usage during similar weather

Sector/Route blockage for J36/J95 departure routes more severe at 2015 UTC than at 1945 UTC

Figure 6. WACU model-derived NY departure flight tracks and available sector capacity at 1945 UTC (A and B, respectively) compared with actual NY departure flight tracks and available sector capacity at 2015 UTC (C and D, respectively). CIWS VIL precipitation is shown in each panel.



	ACTUAL – PHL departure traffic	WACU MODEL – PHL departure traffic
1	**J80 closed** after 2000 UTC PHL departure flight	J80 open, with expanded spacing restrictions, for PHL departures (not full volume); J80 sector < 50% blocked by weather
2	**J80 closed – PHL departures rerouted south**, increasing PHL flight distances as well as delays for traffic nominally using these routes; Most PHL departures forced to remain at airport **Departure delays quickly escalate**: 2000: 45 min; 2025: 75 min 2050: 105 min; 2125: 135 min	**J80 open – volume controlled on other routes**; reduces delay for NY traffic using southbound routes for departure "escape routes" **PHL departure delay queue held in check**
3	**J80 pathfinder released in attempt to reopen route**; convective weather impacts on route and sector availability similar at this time to when route was closed – large delays make route reopening more of a necessity; Route reopens at 2130 UTC	**J80 remains open so PHL pathfinder attempt not required** – traffic managers and controllers avoid time consuming and inefficient pathfinder procedure and PHL delay still well managed

Figure 7. Actual (top) vs. WACU-modeled (bottom) PHL flight tracks at 2030 UTC and 2050 UTC on 27 July 2005. Actual and modeled flight tracks are overlaid atop CIWS Echo Tops. Available sector capacity at 2030 UTC and 2050 UTC, derived from the Wx-RB model, is provided on the right. Specific points of comparison are labeled with numbered triangles and described with more detail in the accompanying table.

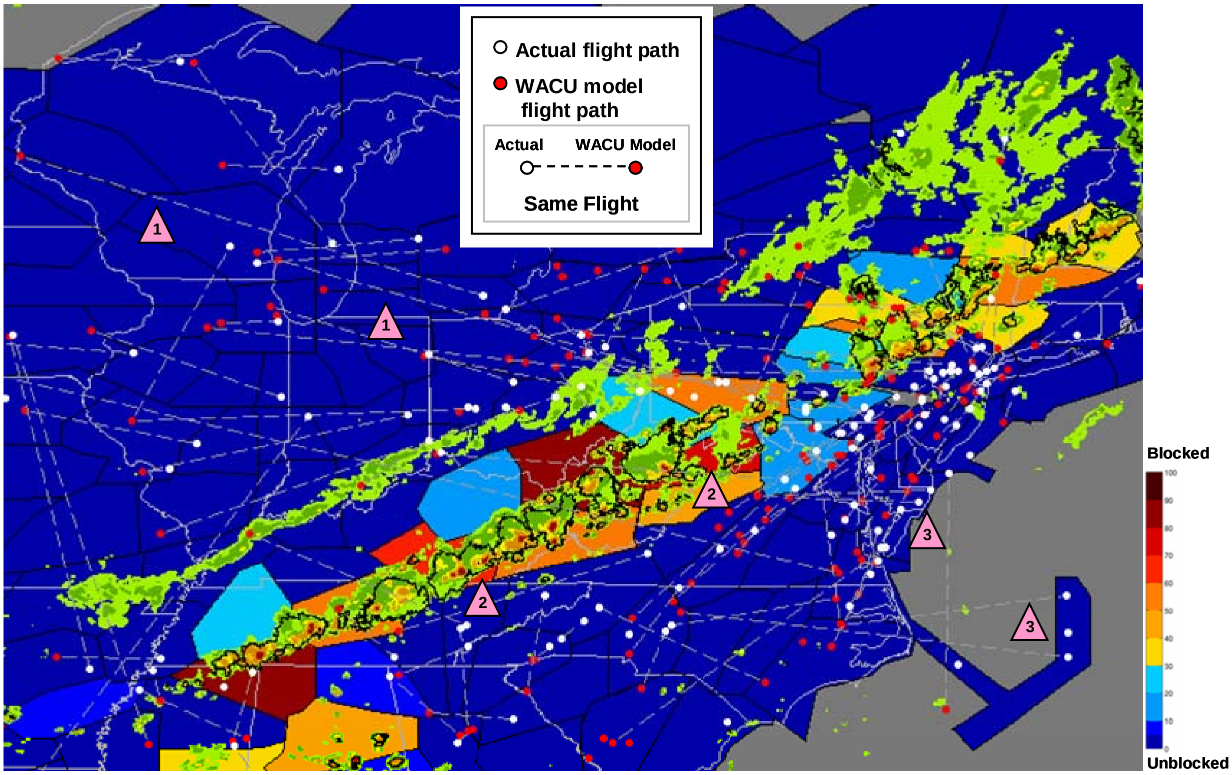


Figure 8. Actual (white) vs. WACU model-derived (red) EWR, LGA, JFK, and PHL airborne departure flights at 2130 UTC on 27 July 2005. Dashed lines connect the same flight. (1) – (3) are referenced in the paper.

3.2.2 Managing Arrival Traffic Demand during Convective Weather Impact Events

Efficient management of traffic arriving in the Northeast U.S. can be difficult, given the often inflexible en route and terminal capacity constraints and near constant air traffic demand. This task becomes much more difficult during convective weather, as decisions to adjust arrival traffic demand based upon available airspace capacity must be made with uncertain weather forecast information at time scales 1-6 hours in advance. Inefficiencies arise when decisions are made based upon incorrect or incomplete weather forecasts or when options to tactically adjust strategic plans to account for time-varying capacity availability are not utilized.

On 27 July 2005, traffic managers devised a plan to implement GDPs at the metro NY airports for expected en route convective weather impacts (i.e., “GDPs in support of SWAP”). Initial plans implemented at 1400 UTC, based on anticipated airspace constraints inferred from the Collaborative Convective Forecast Product (CCFP), called for GDP programs and reduced NY arrival demand to start at 2000 UTC. By 1900 UTC, convective weather development – and the resultant airspace capacity reduction – was more significant than originally anticipated and without arrival flow management initiatives in place, NY arrival traffic demand exceeded available capacity and many aircraft were forced into airborne holding. At this time, NY GDPs were moved up to begin at 1915 UTC (EWR and LGA) and 1945 UTC (JFK) but this did not address the demand/capacity imbalance already impacting the NAS network.

With perfect knowledge of convective weather impacts and time-varying capacity restrictions, the WACU model determined a flight allocation strategy that adequately managed NY arrival traffic demand, prevented airborne holding, and reduced delay (Figure 9A and 9B). WACU model results can also be compared with guidance from candidate weather-ATM decision support tools to determine if plans recommended by the decision support tools would approximate the flight allocation strategy identified by the WACU model. In this example, the CIWS 90 minute Echo Tops Forecast (Dupree et al. 2006) issued at 1820 UTC accurately predicts that the primary NY eastbound arrival routes would be impacted by significant convection after 1930 UTC (Figure 9C). With this information, traffic managers could have revisited

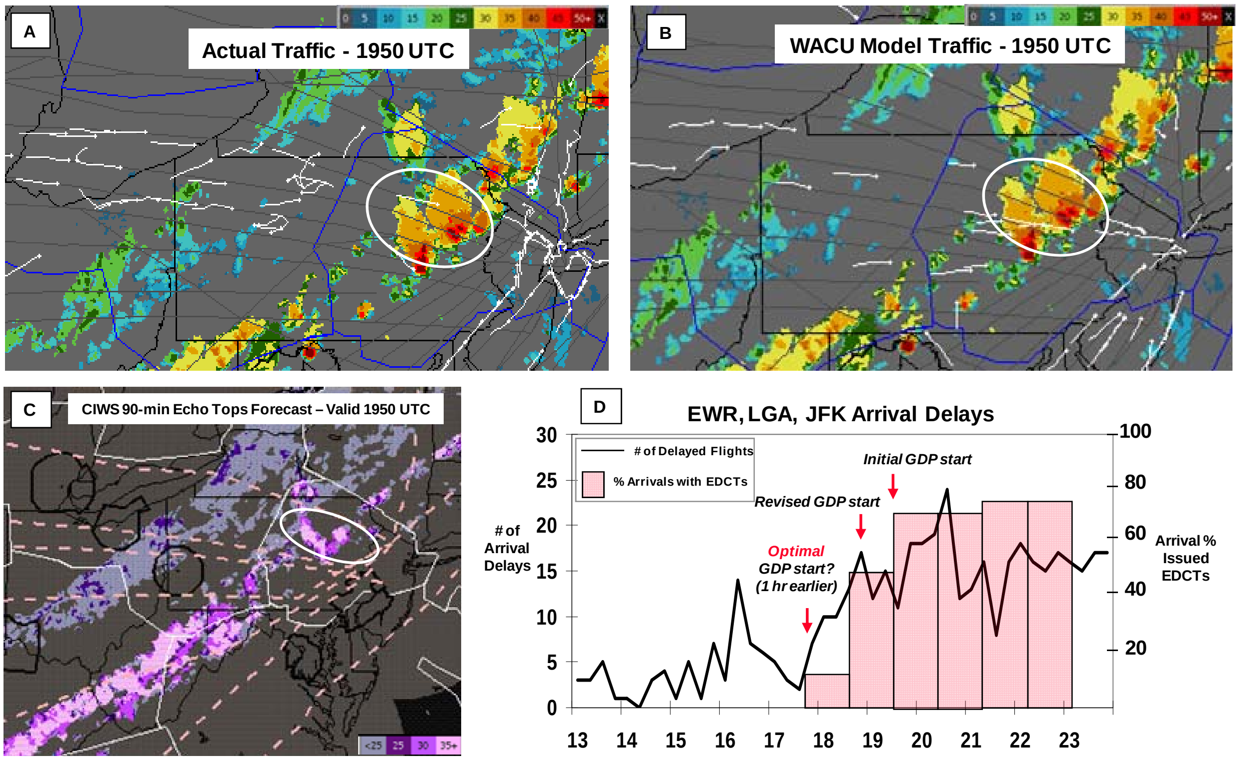


Figure 9. Actual (A) vs. WACU model (B) EWR, LGA, JGK arrival traffic at 1950 UTC on 27 July 2005. Actual and modeled flight tracks are overlaid atop CIWS Echo Tops. The CIWS 90 minute Echo Tops Forecast, issued at 1820 UTC and valid at 1950 UTC, is shown in (C). The circled regions show an area of strong convection impacting the primary NY arrival routes at 1950 UTC (A and B) and the accurate CIWS prediction of this impact 90 minutes prior (C). The relationship of hourly NY delayed arrivals and the number of arrival flights each hour issued GDP Estimated Departure Clearance Times (EDCTs) is shown in (D). The large number of delays and small number of EDCT flights in the 1800 UTC hour suggest that NY arrival traffic was over-delivered, resulting in excessive airborne holding.

GDP strategies – issued at 1400 UTC to begin at 2000 UTC, then revised after 1900 UTC – and revised programs to begin 60-90 minutes earlier (Figure 9D). This tactical adjustment to the strategic plan likely would not have matched the WACU model in eliminating avoidable NY arrival delay, but it would have likely reduced excess airborne arrival demand, airborne holding, ATC complexity and workload, and NY arrival delays.

4. ADDITIONAL WACU MODEL APPLICATIONS

The case study examples just presented demonstrate how the WACU model can be used to:

- Provide a quantitative measure of NAS “”resource utilization” – a desired metric for assessing weather-ATM performance.
- Determine a weather impact severity metric – unavoidable delay – that accounts for not only convective weather, but its impact on ATC network operations as well.
- Review daily weather-ATM operations, from top-level strategic plans, to individual traffic management initiatives, to routing decisions for individual flights, for a “next-day” assessment of traffic management performance.

Additional applications of the WACU model are described in this section.

4.1 Identifying Weather-ATM “Benefits Pool” for New Tool Business Case Development

In recent years, several new FAA weather-ATM decision support tools have been developed and tested. As part of the performance evaluation effort, the FAA requires a detailed assessment of the potential benefits associated with each weather decision support tool [e.g., Robinson et al. (2008); Robinson et al. (2006); Department of

Transportation (2006); Allan and Evans, (2005); Robinson et al. (2004)]. In many cases, significant terminal and en route delay reduction benefits were indentified. A persistent question from FAA investment analysis assessments is what the ratio of cumulative delay-saving benefits to the total "benefits pool". Specifically, there is concern that large benefits savings assigned to individual weather decision support tools (and collectively for the suite of tools under development) may exceed the total pool of weather-related delays (or at least suggest an unrealistically large percent reduction of the total potential avoidable delay). Objective determination of the potential pool of avoidable weather delays would help to validate the estimated benefits from weather-ATM decision support tools under review.

WACU model estimates of avoidable and unavoidable delay could be used to determine the total benefits pool available for weather decision support tools. Weather tool "before/after" benefits estimates using the WACU model would also provide objective results that effectively normalize for case-to-case (or year-to-year) differences in air traffic demand, weather, and airspace capacity[8].

4.2 Quantify Operational Impacts Resulting from Expected NAS Evolution

Over the next 15 years, several changes to the NAS – some of which have already begun - are expected:

- Commercial air traffic demand is expected to increase by 55% (FAA, 2007)
- General aviation operations are expected to increase by 59% (FAA, 2007)
- Continued evolution in aircraft fleet mix [e.g., recent rise and further increase in use of regional jets, introduction of Very Light Jets (VLJs)]
- Reduced minimum air traffic separation and potential increase in airspace capacity with deployment of the Automatic Dependent Surveillance Broadcast (ADS-B) system (www.adsb.gov)
- En route airspace redesigns and new terminal runways
- Increased use of secondary airports, primarily by low-cost air carriers

All of these changes are expected to have a profound effect on NAS operations and efficiency. However, it is not quantitatively understood how the NAS network will be affected, given the complex inter-relationship of all these variables. Moreover, the severity of convective weather disruptions in the future NAS network is not well understood.

The WACU model could potentially be used to quantitatively measure the effect of specific changes to the NAS. For example, for a given convective weather event (or even a clear-weather day), the model could be run once with the present day traffic demand and then again with 10%, 25%, 50% increases in demand. The difference in the estimated unavoidable delay compared to the control run would be considered a quantitative measure of the impact of increased traffic demand.

Multiple NAS changes could also be modeled simultaneously to identify potential constructive (or destructive) weather-ATM network effects. These types of modeling efforts may help the FAA with resource allocations and identifying needs for additional research and development.

4.3 Improved Public Awareness of Weather-ATM Performance

Annual differences in commercial aviation delays are often presented without noting largely uncontrollable differences in the traffic flow management environment (e.g., network traffic demand and weather). This results in incomplete and sometimes unfair assessments of FAA or commercial airline performance.

WACU model estimates of unavoidable and avoidable delay can be used as objective measures of ATM performance that account for differences in weather impacts and traffic demand. Monthly estimates of unavoidable delay and modeled-derived ratios of avoidable/unavoidable delay could be used to note differences in the severity of weather impact events and more clearly describe the efficiency of air traffic operations. Two examples of the public awareness benefits of unavoidable delay estimates include improved understanding of air traffic delays for passengers and a more complete description of commercial airline operational performance for company stockholders.

---

[8] Before and after "baseline" comparisons of the capabilities of weather-ATM decision support tools have proven extremely difficult because the scalar metrics typically used for these analyses (e.g., ASPM delay statistics) do not adequately account for differences in air traffic demand (e.g., scheduled operations, high-altitude air traffic volume, etc.), weather characteristics (e.g., severity, duration, coverage, location, etc.), or ATM planning techniques (e.g., GDPs in support of SWAP vs. Airspace Flow Programs (AFP)) to provide results that isolate differences in NAS network resource utilization attributed solely to the use of the weather tools under review.

4.3.1 Summer 2007 air traffic delays

The vast majority of air traffic delays during the summer months are the result of convective weather. Media accounts of U.S. air traffic delays during June – August 2007 note an increase in delays compared to previous years, but provide no quantitative measure for convective weather impacts in either year (e.g., USA TODAY, 2007 – "Air Travelers Suffer Summer of Pain"). These types of comparisons are incomplete because they do not normalize for delay causality. This is a potential disservice to both the flying public and the NAS traffic management community because delay comparisons that do not account for differences in the NAS operational environment do not adequately represent the performance (good or poor) of the U.S. aviation system.

Unavoidable delay statistics generated by the WACU model would help the FAA more accurately inform the public about the proportion of total weather-induced air traffic delay for which there is no current remedy. Year-to-year comparisons of monthly weather delays accompanied (or normalized) by a measure of unavoidable delay would provide a more robust, meaningful estimate of weather-ATM performance during the summer storm season.

4.3.2 Clarification of Delta Air Lines monthly revenue loss

In 2006, Delta Air Lines Inc. reported losses of $11 M during the month of August, the equivalent of 6 cents per share for company stockholders (International Business Times, 2006). On receipt of this news, investments in Delta decreased by 20%.

The largest operational hub for Delta is Atlanta Hartsfield-Jackson International Airport (ATL). During August 2006, ATL airport and the Atlanta Air Route Traffic Control Center (ARTCC) airspace were significantly impacted by convective weather (Figure 10). The FAA Operations Network (OPSNET) reported 40,000 delays for ATL airport in August 2006. It can therefore be assumed that Delta operations during this month were severely disrupted by thunderstorm activity. How much of the company's $11 M monthly loss was caused by weather and unavoidable delay?

Unavoidable weather-ATM delays calculated by the WACU model could be used to better inform stockholders on airline company performance. If increased operating costs (fuel, crew, ground support), resulting from increased delays/cancellations in August 2006, were the primary cause for Delta's $11 M loss, and if these delays could have been shown by the WACU model to be primarily unavoidable, Delta may have been able to show their shareholders that losses were not the result of airline inefficiencies but rather uncontrollable NAS-wide impacts. This information may have helped to steady Delta stockholder confidence when August 2006 losses were reported.

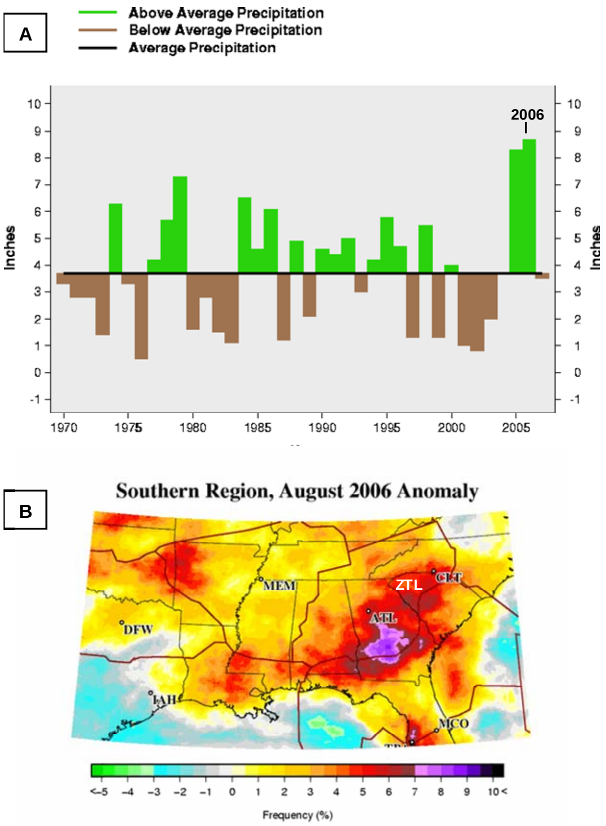
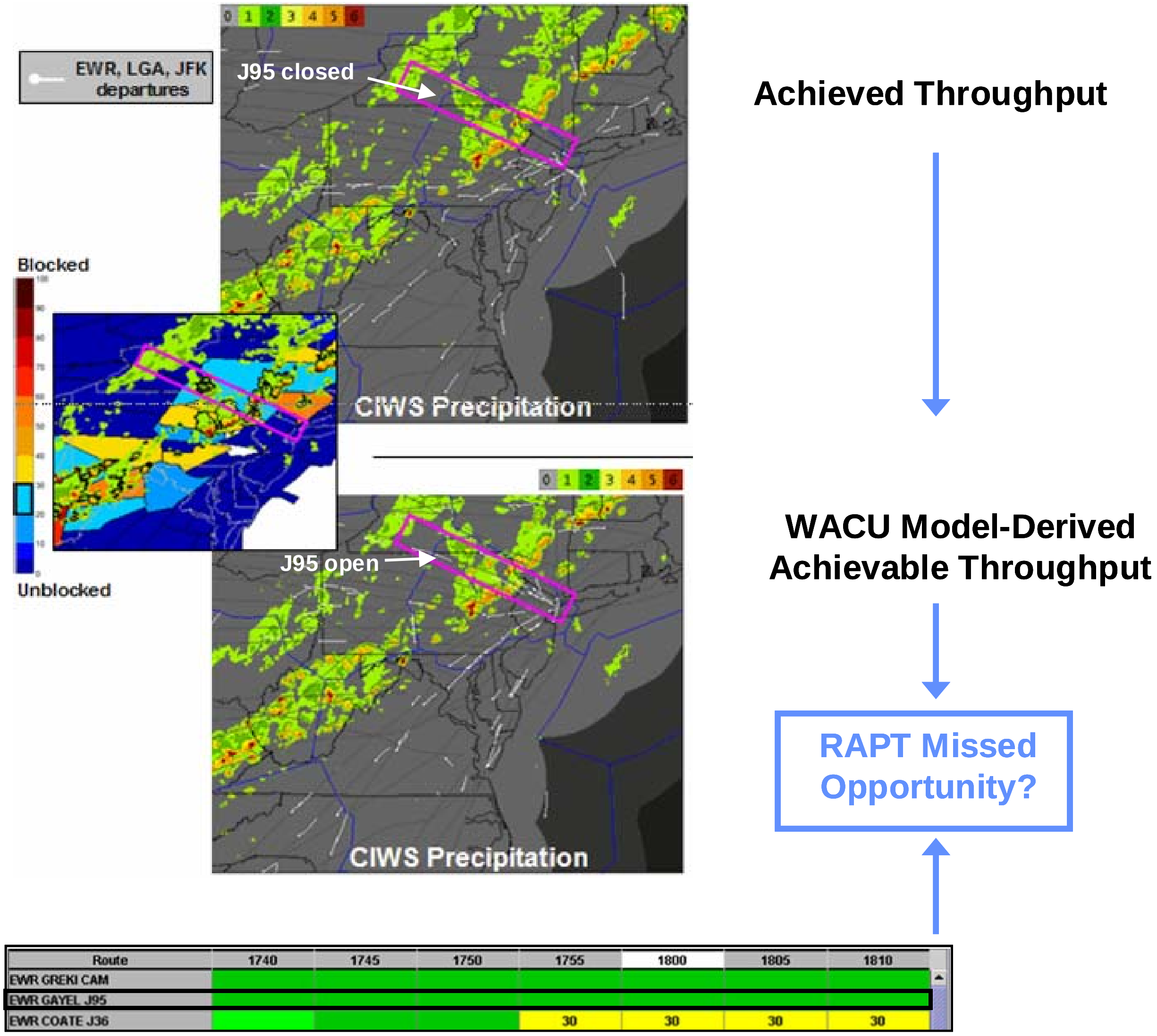


Figure 10. (A) August precipitation from 1970-2007 at ATL airport, in terms of departure from average (in inches) and (B) August 2006 anomalous frequency (above/below historical average) of issued Significant Meteorological Information advisories for convective weather (C-SIGMET) across the southeast U.S. (A) and (B) show significantly above average precipitation and thunderstorm activity at ATL airport and ZTL airspace during this month. Data are provided by the NOAA National Climatic Data Center (NCDC).

Delta and other commercial airlines could also use the high-resolution WACU model data to review actual vs. modeled flight tracks – highlighting their company's flights – to review FAA weather-ATM practices. In this manner, an airline can help determine opportunities for improved routing and scheduling practices during convective weather (thus improving airline operational efficiency) and ensure equitable traffic flow management strategies exist among other airlines.

4.4 Improved Traffic Management Training

Case study examples presented in Section 3 have already demonstrated how the WACU model may be used for next-day reviews of implemented weather-ATM strategies and identification of potential missed opportunities for improved NAS network resource utilization. Repeated observations of alternative weather-ATM approaches derived from the model may help to improve the recognition-primed decision-making model used by air traffic managers during severe weather (e.g., Evans and Robinson, 2008; Klein, 1998).



Route	1740	1745	1750	1755	1800	1805	1810
EWR GREKI CAM	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR GAYEL J95	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR COATE J36	🟩	🟩	🟩	🟨 30	🟨 30	🟨 30	🟨 30

RAPT guidance – shows J95 as viable route

Figure 11. Concept for using WACU Model to support RAPT Missed Opportunity Scenario Training. Canonical example where departure route (J95) is closed (top), but WACU Model devises plan that utilizes available airspace and keeps J95 open (bottom). RAPT guidance at that time shows J95 as a viable departure route (green or "clear" in RAPT route blockage timeline) – matching WACU model assessment, thus suggesting this was a missed opportunity to use RAPT to increase departure capacity.

Weather-ATM missed opportunities determined objectively with the WACU model can also be used to explicitly support new weather decision support tool training. In fact, the WACU model will be used in 2008 to support Missed Opportunity Scenario Training (MOST) for the Route Availability Planning Tool (RAPT – DeLaura et al. 2008). As part of an expanded RAPT interactive training program (Robinson and Evans, 2008), missed opportunities to increase NY departure capacity through the use of RAPT will be objectively determined by the WACU model, then presented to operational traffic managers and airline dispatch coordinators for discussion (Figure 11). An improved understanding of actual events where RAPT usage may have improved departure flow management efficiency is expected to increase RAPT delay reduction benefits (Robinson et al. 2008). Using the WACU model to objectively identify these events will provide credibility and an unbiased assessment useful for both training as well as follow-on RAPT benefits studies.

5. SUMMARY

The U.S. National Airspace System (NAS) operates as a complex interconnected network where demand and capacity can vary substantially over short periods. Efficient management of the NAS network is particularly difficult during convective weather, given the uncertainties associated with convective weather forecasts and the difficulty in translating weather impacts into statements of impacted airspace capacity and optimal weather-ATM strategies. There is currently great interest in improving the ability to quantitatively assess how well ATM services are provided as new weather-ATM decision support capabilities are made available. Increased scrutiny of air traffic operations, because of increased delays in recent years has also increased the need for quantitative assessments of NAS resource utilization efficiency.

A model has been developed to assess how available airspace capacity could have best been utilized during convective weather events. The Weather-ATM Capacity Utilization (WACU) model uses time-varying capacity reduction estimates (caused by convective weather) and integer programming and schedule optimization techniques to automatically generate broad-area ATM strategies that optimize the use of available capacity. Output from the WACU model include a quantitative estimate for unavoidable delay, as well as individual flight tracks that can be reviewed in a playback mode and compared with actual traffic flows to assess individual traffic management decisions.

Model results from three convective weather case study events were presented, each with different types of thunderstorm impacts and implemented weather-ATM strategies. Case study results demonstrate how avoidable and unavoidable delays estimates derived by the WACU model can be used to assess the performance of weather-ATM strategies and/or potential options for alternative decisions. Comparing actual vs. modeled flight tracks for the 27 July 2005 squall line even reveals how the WACU model can be used for post-event (next-day) traffic management reviews and help identify missed opportunities for improved tactical and strategic weather-ATM decisions. Model results can also be cross-referenced against alternative weather-ATM decision support tools [e.g., CIWS Echo Tops Forecast or the Route Availability Planning Tool (RAPT)] to objectively determine the potential benefits provided by improved information.

The WACU model can be used to determine the aggregate weather delay that could potentially be avoided through the use of improved weather-ATM decision support tools. This avoidable delay estimate could serve as a measure of the total “benefits pool” available for the cost/benefit business-case development of new decision support capabilities. The model could also support quantitative studies of the effects on resource utilization capabilities caused by expected changes in the NAS (particularly during convective weather), such as increased air traffic demand, continued aircraft fleet mix changes, revised aircraft separation restrictions, en route airspace redesigns, and new airport runways. Results in these studies could help the FAA more effectively allocate resources and direct research and development efforts.

Improved public awareness and increased understanding of NAS delays is another potential benefit of WACU model applications. Media accounts of general increases in air traffic delays, accompanied by event, month, or seasonal estimates of model-derived unavoidable delays – which account for delay causality - may more adequately represent the performance (good or poor) of the U.S. aviation system. In this same manner, commercial airline companies could use WACU model data for more detailed interpretations of revenue performance.

The WACU model can support weather-ATM training. In 2008, the model will be used to objectively identify potential missed opportunities for RAPT-derived NY departure flow management improvements. These data will be used as part of the RAPT Missed Opportunity Scenario Training (MOST) Program, where face-to-face discussions with operational traffic managers about the additional uses of RAPT are expected to result in increased NY delay reduction benefits.

Several enhancements to the WACU model are planned or under investigation. The improved estimates of en route capacity in convective weather described in Martin et al. (2007) will be used by the WACU model in the future. The current route structure database in the model for available reroute alternatives needs to be expanded to increase alternative routing options. Additional secondary airports such as White Plains, NY (HPN) and Stewart Airport (Newburgh, NY) need to be explicitly considered since the traffic from such airports is an important consideration in New York airspace congestion. The replacement of the standard, yet flawed, ETMS Monitor Alert Parameter (MAP) values for estimated clear-weather sector capacity in the WACU model with en route sector capacity estimates based on a macroscopic controller workload model approach developed by Welch et al. (2007) is under consideration. Finally, efforts will be made to investigate optimized terminal weather-ATM strategies when convective weather impacts are present within the terminal airspace of large airports.

6. REFERENCES

Allan, S., and J. Evans, 2005: Operational Benefits of the Integrated Terminal Weather System (ITWS) at Atlanta, MIT Lincoln Laboratory Project Report ATC-320.

Bertsimas, D. and S. Stock-Patterson, 1998: The Air Traffic Flow Management Problem with En Route Capacities, Operations Research, 46, 406-422.

Boone, D., R. McGuire, T. Berry, and M Yankey, 2006: S2K/RTCA Customer Metrics Working Group Discussion Material, presentation to the RTCA Airspace Management Steering Committee (http://www.rtca.org/comm/Committee.cfm?id=52)

DeLaura, R., M. Robinson, R. Todd, and K. MacKenzie, 2008: Evaluation of Weather Impact Models in Departure Management Decision Support: Operational Performance of the Route Availability Planning Tool (RAPT) Prototype, 13th Conference on Aviation, Range, and Aerospace Meteorology, AMS, New Orleans, LA.

Department of Transportation, 2006: Weather and Radar Processor (WARP) Investment Summary and Justification. Available at: http://www.dot.gov/exhibit300/faa216warp.htm

Dupree, W., M. Robinson, R. DeLaura, and P. Bieringer, 2006: Echo Tops Forecast Generation and Evaluation of Air Traffic Flow Management Needs in the National Airspace System, 12th Conf. on Aviation, Range, and Aerospace Meteorology, AMS, Atlanta, GA.

Evans, J. and M. Robinson, 2008: Application of Models for Decision-Making in Difficult Environments to Improve Air Traffic Management during Severe Convective Weather, 13th Conference on Aviation, Range, and Aerospace Meteorology, AMS, New Orleans, LA.

FAA, 2007: FAA Aerospace Forecasts Fiscal Years 2007-2020. Available at: http://www.faa.gov/data_statistics/aviation/aerospace_forecasts/2007-2020/media/FAA%20Aerospace%20Forecasts%20FY%202007-2020.pdf

International Business Times, 2006: Delta Reports $11 M Loss for August. Available at: http://www.ibtimes.com/articles/20060929/delta-earnings-report.htm

Klein, G., 1998: Sources of Power: How People Make Decisions, MIT Press, Cambridge, MA.

Martin, B., J. Evans, and R. DeLaura, 2006: Results of an Exploratory Study to Develop a Model for Route Availability in En Route Airspace as a Function of Actual Weather Coverage and Type, MIT Lincoln Laboratory Project Report NASA/A-7.

Martin, B. 2007: Model Estimates of Traffic Reduction in Storm Impacted En Route Airspace, 7th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Belfast, Ireland.

Robinson M. and J. Evans, 2008: An Interactive Training Approach to Support the Operational Use of Air Traffic Management Convective Weather Decision Support Tools, 13th Conference on Aviation, Range, and Aerospace Meteorology, AMS, New Orleans, LA.

Robinson M., R. DeLaura, J. Evans, and S. McGettigan, 2008: Operational Usage of the Route Availability Planning Tool during the 2007 Convective Weather Season, 13th Conference on Aviation, Range, and Aerospace Meteorology, AMS, New Orleans, LA.

Robinson, M., J. Evans, and T. Hancock, 2006: Assessment of Air Traffic Control Productivity

Enhancements from the Corridor Integrated Weather System (CIWS), MIT Lincoln Laboratory Project Report ATC-325.

Robinson, M., J. Evans, B. Crowe, D. Klingle-Wilson and S. Allan, 2004: CIWS Operational Benefits 2002-3: Initial Estimates of Convective Weather Delay Reduction, MIT Lincoln Laboratory Project Report ATC-313.

USA TODAY, 2007: Air Travelers Suffer Summer of Pain. Available at: http://www.usatoday.com/money/industries/travel/2007-09-03-summer-air_n.htm

Welch, J., J. Andrews, and B. Martin, 2007: Macroscopic Workload Model for Estimating En Route Sector Capacity, 7th USA/Europe ATM 2007 R&D Seminar, Barcelona, Spain.