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Evaluation of Convective Weather Impacts on US and European Airports*

Gabriele Enea, Margita Pawlak & Tom Reynolds
Air Traffic Control Systems Group
MIT Lincoln Laboratory
Lexington, MA, USA

Alexander Lau
Institute of Air Transport
German Aerospace Center (DLR)
Hamburg, Germany

Dave Knorr & Martin Durbin
NextGen System Analysis & Modeling Division
Federal Aviation Administration (FAA)
Washington, DC, USA

Peter Roth, Stefan Schwanke, & Sanjay Dussoye
Deutsche Flugsicherung GmbH (DFS)
Germany

Abstract—**In this paper, the impact of convective weather on two major hub airports in the Unites States and Europe is compared. First, the delays caused by weather are analyzed and it was found that it is one of the major sources of delays. Two different approaches to study the problem are then presented. In the US, a study is presented to identify a pool of potential additional departures that could be achieved during convective weather days in Atlanta by providing traffic managers with enhanced information not available today. Then, an operational overview is presented of the procedures used during convective weather days in Munich. This study is complemented by an approach to identify convective weather days in Munich. The US and European approaches are compared next and lessons learned are discussed. By comparing best practices and experiences during challenging weather conditions from the US and Europe, valuable insights can be obtained for any Air Navigation Service Providers.**

Keywords-Convective Weather; Departure Throughput; Airport Delays.

I. INTRODUCTION

Convective weather impacts air traffic both in Europe and in the United States (US) causing delays and cancellations at major airport hubs. Air Navigation Service Providers (ANSPs) try to mitigate the impacts of convective weather and maximize the use of the reduced capacity during these challenging conditions. More work is still necessary to support Air Traffic Control (ATC) in planning, managing and implementing effective mitigation strategies, but a first necessary step is to identify the pool of potential benefit opportunities associated with existing and new capabilities that could lead to operational improvements.

By comparing best practices, benefits analysis and ATC strategies during convective weather at major airports in Europe and in the US, this paper aims to provide valuable information to all ANSPs and to the broader ATC community. To achieve this goal, the paper presents two different approaches and related studies funded by the US Federal Aviation Administration (FAA) Nextgen System Analysis and Modeling Division and by the German Federal Aviation Research Programme. The two studies focus on Atlanta Hartsfield-Jackson (ATL) and Munich International (MUC) airports respectively. Using a bottom-up, data-rich approach, the former study performed by MIT Lincoln Laboratory used historical weather data to identify unused departure opportunities that could have potentially been achieved in ATL if additional information had been provided to the air traffic managers. Using a top-down approach, the latter study performed by DLR, interviewed MUC air traffic controllers to identify best practices and operational procedures during convective weather days. This study was also complemented with a study of convective weather days that significantly impacted MUC in 2019.

The objectives of the paper are to compare how convective weather impacts US and European airports differently; how weather-related delays are classified and what are the best practices in terms of weather forecasts and decision-support-tools. Eventually, studies such as this can also be used to help

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inform future technical requirements and international harmonization for such tools.

The remainder of the paper is organized as follows: Section II presents a brief summary of previous related research. Section III gives a description of the Atlanta and Munich airports and impacts that convective weather has on them. Section IV describes the methodology used to quantify the additional departure pool in Atlanta and the ATC interview study is described in Section V. Section VI presents an analysis of weather days in Munich. A comparison of the US and European approaches is presented in Section VII. The paper ends with a discussion of lesson learned and conclusions in Section VIII.

II. Previous work

The impact of convective weather on airport operations has been extensively studied because it is a major cause of delays and disruptions. Convective weather reduces the terminal area airspace capacity and therefore the ability of controllers to maneuver and sequence aircraft before landing. Moreover, usually manifesting with precipitation, ceiling, visibility and winds, it reduces the capacity of the runway systems.

EUROCONTROL developed the Air Traffic Management Airport Performance (ATMAP) algorithm to describe weather conditions at European airports that are used to classify weather events and define operational impacts [1]. ATMAP was used in [2] to classify European airports based on the type of weather affecting them. Overall, in 2018, Munich (Germany) and Oslo (Norway) had the highest number of weather impacts. Dusseldorf (Germany) had the largest share of dangerous phenomena including thunderstorms. As expected, the authors also found a strong correlation between weather events, and delays and cancellations for both departures and arrivals.

Odoni *et al.* quantified the impact of progressively deteriorating weather conditions on airport capacity in [3]. Benchmarking airports from the United States (Newark, EWR) and Europe (Frankfurt, FRA), they found that with weather impact (ceiling and visibility), the hourly throughput at EWR decreased almost 15%, while in FRA the decrease was 9%. The reason being that EWR maximum demand was set close to the Visual Meteorological Conditions (VMC) (good visibility) while Frankfurt capacity was set close to the Instrument Meteorological Conditions (IMC) (low visibility). Therefore, EWR was more susceptible to the impact of weather events. A similar conclusion was presented in [4], where authors compared Air Traffic Management (ATM) operational performance in the United States and Europe. It was also reported that, in general, US airports are also more susceptible to convective weather impacts than European counterparts, both because of the prevalence of weather events and the way the airport capacity is set.

Perhaps for this reason, several studies were conducted to identify the benefit of improved weather forecasts for ATM operations in the United States. In [5] a model to predict pilot behavior around convective weather at low altitudes, therefore more applicable to airport operations, was presented. The Convective Weather Avoidance Model (CWAM) was extended to include low-altitude flights which typically occur below the tops of convective weather and have slightly different operational constraints. This model is also applicable to low altitude escape routes, sometimes used to reduce the impact of convective weather on the terminal area. The performance of the low altitude CWAM was compared to the traditional version by identifying the correct number of aircraft reroutes, noticing that the former performs better.

Improved weather models are most valuable to ATC when the information is translated into operational impacts. In [6] a connection between the uncertainty in the thunderstorm forecasts and the operational decisions based on this information was developed using the New York airports as a case study. The study acknowledges the challenges of Air Traffic Management during off-nominal weather and the difficulty of interpreting and managing uncertainty necessary to plan departure routes in these conditions. In [7] a detailed description is given of a convective weather event in New York and its effect on departure throughput, as well as the response of traffic managers and the potential effect of using a decision support tool such as the Route Availability Planning Tool (RAPT) [8] on system performance. A key challenge identified in the paper is that a static route definition of limited length into downstream airspace does not capture the full range of operational airspace use during highly dynamic convective conditions. In the ATL study presented in this paper, where route adherence is less strict than in New York, this is a bigger factor.

Based on the issues discussed and starting from a previous study from the same authors [9], this paper compares approaches in studying operational impacts caused by convective weather in the US and Europe. These impacts will be discussed in the next section.

III. Weather Impacts in Atlanta and Munich

In this section, a brief description of the airports which are the subject of this paper (Atlanta in the US and Munich in Germany) and their delay statistics will be presented.

A. Atlanta (USA)

In 2021, Atlanta Hartsfield-Jackson (ATL) was the busiest airport in the world for number of yearly movements [10]. With five runways oriented east to west, it is a major hub for Delta Air Lines which is one of the largest carriers in the United States. In the summer months, ATL is frequently impacted by thunderstorms. As shown in Figure 1, in 2020 and 2021 when the total volume of operations decreased due to the COVID pandemic, almost 80% of total delays in ATL were caused by weather impacts [11]. In 2021, 50% of the delays affected departure operations with a total of almost 40,000 minutes of departure delays. This is well below the 2019 values, but in 2021, ATL was back to only 80% of the number of operations before the pandemic. Even then, almost 60% of all delays in ATL were caused by weather. Given these statistics, ATL is a good site to study weather impacts on airport operations in the US.

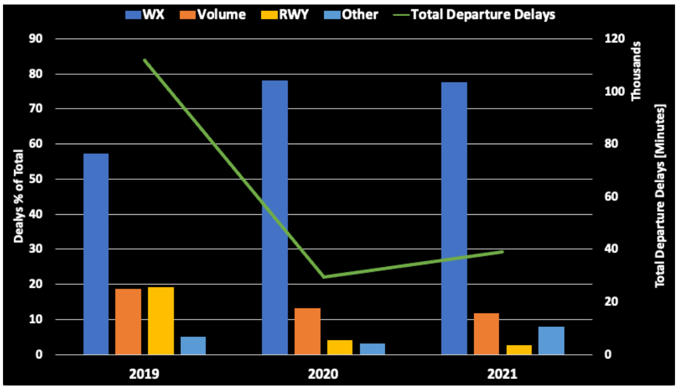

Figure 1. Delay causes in ATL and total departure delays (green line) from the FAA Aviation System Performance Metrics (ASPM) database (2019-2021). Wx = Weather impacts, RWY = Runway impacts.

B. Munich (Germany)

In 2019, Munich International Airport (Franz Josef Strauß), with nearly 48 million passenger movements and about 18,500 air freight tons, was Germany's second busiest airport after Frankfurt/Main. On average it processed 567 movements per day, making it number 6 of the top 10 airports in Europe.

Using the EUROCONTROL Central Office for Delay Analysis (CODA) database [12], Figure 2 shows the percentages of all International Air Transport Association (IATA) primary departure delay causes, which integrate several IATA delay codes. IATA delay is tracked from the perspective of an airline, which reports all *actual* experienced departure delay and assigns it to 99 delay codes [13].

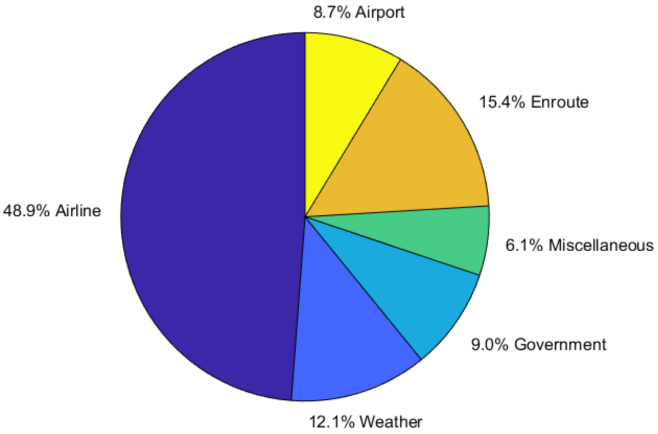

Figure 2. MUC primary IATA departure delay causes 2019. Data: EUROCONTROL CODA database.

The primary cause of delay (48.9%) at MUC is attributed to airline operations. MUC, as a hub airport, plays an important role for interconnecting flights of several major airlines operating at the airport. Delays generated through a multitude of interconnecting flight legs within an airline`s hub-and-spoke network will typically appear at a hub airport like MUC. An *Airline* delay in MUC could be caused by a departure delay at any origin airport resulting in such a high percentage of the overall delay. This value, like all others, includes traffic from all operating airlines at MUC in 2019. The percent of departure delays due to enroute adverse impact and delay cumulation not being compensated by ground operations is 15.4%. The third main cause of departure delay is weather with 12.1%.

As will be shown later in the paper in more detail, MUC is particularly affected by weather delays during the summer months, making it a very good case for this study. In the next sections, different approaches to study weather impacts at ATL and MUC will be presented.

IV. US BOTTOM-UP APPROACH

The high-level shortfall analysis to identify the pool of potential benefit opportunities associated with existing and new weather capabilities that could lead to additional departure opportunities in ATL followed a similar methodology to the study applied to the New York Metroplex area presented in [9]. In New York, Traffic Managers have the Route Availability Planning Tool (RAPT) that supports them in identifying departure routes out of the local airports free from convective weather. RAPT is not available in ATL, so additional steps were necessary in this study. The multi-step methodology is summarized in Figure 3.

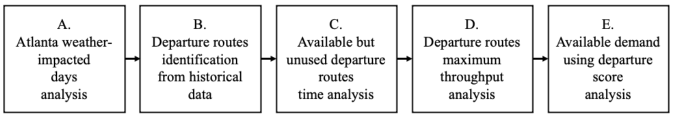

Figure 3. Study analysis methodology.

Different from the study in New York, a database of weather-impacted days was not available for Atlanta. Therefore, the first step (A) was to identify days from historical data that impacted Atlanta departure operations. Similarly, since RAPT is not adapted for Atlanta routes, these needed to be created from scratch using historical flight data (B). The next step (C) was to identify unused routes that could have provided a departure outlet but were not used. These were quantified as opportunity time periods. These time periods had to be converted to actual departure opportunities, and to do so, a measure of hourly route throughput was defined (D) using historical data. Lastly, it needed to be verified that demand was available to take advantage of the departure opportunity (E). The departure score was used as a proxy for the available demand. Detailed descriptions of each step will be presented next.

A. Atlanta weather-impacted days analysis

Massachusetts Institute of Technology (MIT) Lincoln Laboratory produces the Corridor Integrated Weather System (CIWS) which is a 2-hour forecast product, and the Consolidated Storm Prediction for Aviation (CoSPA) [14] which is an 8-hour forecast, both of which are used by air traffic controllers and managers in the US. Historical data from CIWS and CoSPA in combination with the ASPM Departure Score metric described in Section IV.E were used to identify weather impacted days in ATL in 2019. Using the Vertical Integrated Liquid (VIL) for extended periods time (more than 2 hours) as the main measure of weather impacts on Atlanta departure routes, thirty-seven days were identified during the convective season of 2019 (March 1st to September 30th). These days were used to identify potential departure opportunities.

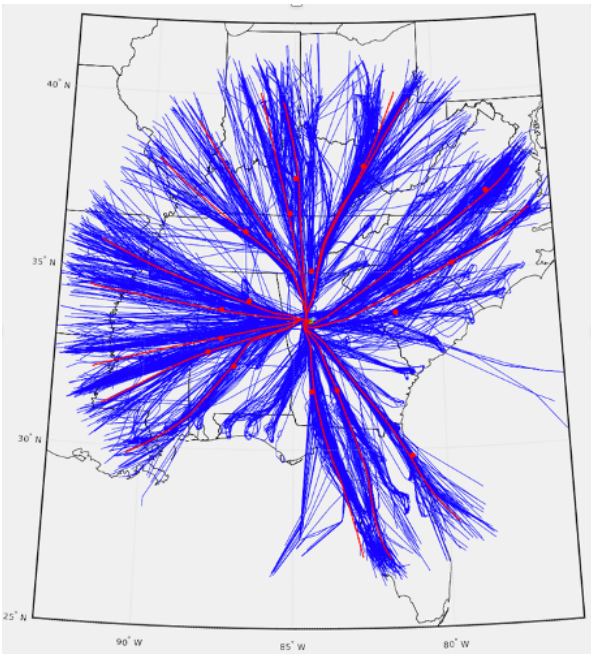

Figure 4. ATL departure routes used for the analysis.

B. *Departure routes identification from historical data*

To identify the departure routes in ATL, data from Standard Instrument Departures (SIDs), the FAA Traffic Flow Management System (TFMS), a waypoints database and filed flight plans were used. Processing these data, plots such as Figure 4 were generated which identified centroids (in red) of the clusters containing the main departure routes (in blue) out of the airport. A total of 14 routes were adapted for ATL for this analysis.

C. *Available but unused departure routes time analysis*

To identify the departure opportunities, a RAPT-like visualization of the salient information necessary was developed as presented in Figure 5. The weather impact on the routes is represented by the color coding, red (closed), yellow (partial impact) and green (open). Moreover, the thickness of the route represented when the route was under or overutilized compared to the average usage (flights per 15 minutes along the route). Lastly, to identify periods of opportunities with demand available on the ground, the Departure Score was visualized on the top of the plot. This will be discussed in more detail in section E.

The integrated visualization of the weather data, with weather impacts on the route utilization and available demand, constituted a novel contribution of the work presented here. This capability represents a RAPT-like historical data tool that is relatively easy to transfer to other airports in the US or wherever similar data can be obtained.

Moreover, for each adapted route, the tool records the Post-Impact Green (PIG) timer summary. A PIG is recorded every time a route has turned from red (closed) to green (open). The PIG times are recorded for a maximum of 180 minutes following a route becoming green (with five minutes rounding error). In addition to the PIG start/end time and length of the PIG period,

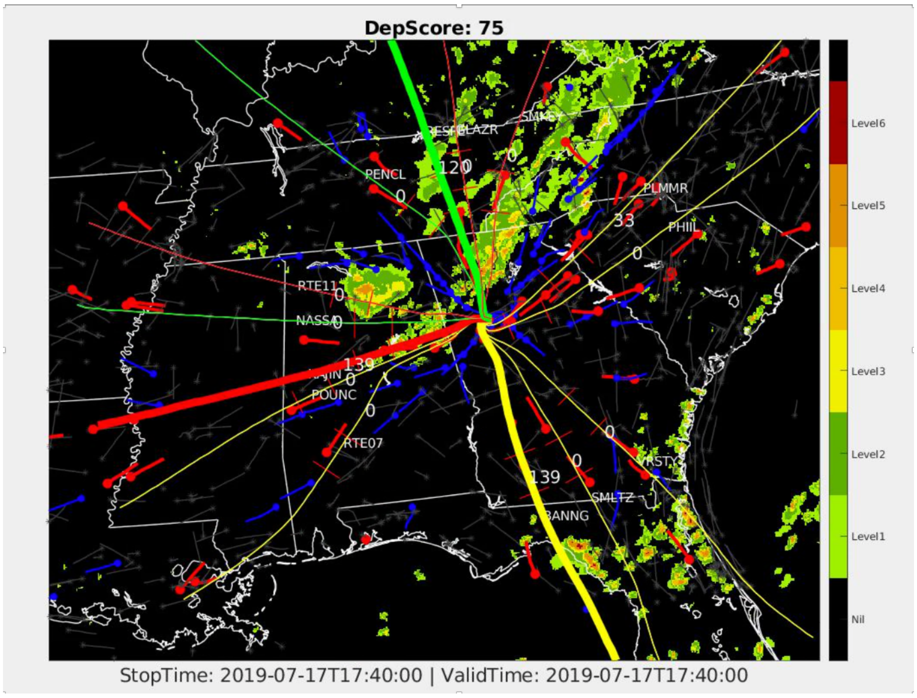

Figure 5. Integrated visualization tool developed for the ATL analysis.

the tool keeps track of when the first flight used the route after it was free from weather (green). This is captured in the PIG Time to First Departure (TFD) metric. The number of flights using the route each hour of the PIG period is also counted for the three hours following the PIG start time or until weather impacts the route again.

TABLE I. EXAMPLE POST-IMPACT GREEN (PIG) TIMER SUMMARY.

20190414 Route	PIG Start (UTC)	PIG End (UTC)	PIG Period (Min)	PIG TFD (Min)	Total Departures			
					0-1 Hr PIG	1-2 Hr PIG	2-3 Hr PIG	Total PIG Period
SMKEY	1700	1940	160	10	2	4	n/a	6
	2600	2900	180	5	6	12	4	22
PLMMR								
PHIIL								
VRSTY	2835	3000	85	15	2	n/a	n/a	2
SMLTZ	2710	3000	170	5	7	1	n/a	8
BANNG	2510	2810	180	40	2	4	4	10
RTE07	1700	2000	180	65	0	3	1	4
	2345	2645	180	30	2	0	2	4
POUNC	1700	2000	180	10	2	1	1	4
	2335	2635	180	60	0	2	0	2
KAJIN	1700	2000	180	5	1	6	1	8
	2330	2630	180	40	1	4	2	7
NASSA	1700	2000	180	0	2	4	4	10
	2330	2630	180	5	4	7	2	13
RTE11	1700	2000	180	5	2	4	4	10
	2330	2630	180	0	10	7	4	21
PENCL	1700	2000	180	0	2	0	11	13
	2330	2630	180	10	11	4	3	18
RESPE	2330	2630	180	0	7	4	3	14
GLAZR	1700	1810	70	70**	0	n/a	n/a	0
	2330	2630	180	15 **=No Depart	6	5	3	14

Table I gives the PIG summary from May 14 2019 for Atlanta. For the highlighted KAJIN route, the PIG time started at 23:30 UTC and ended at 26:30 (May 15 02:30 UTC). This PIG lasted for 180 minutes, and the TFD was 40 minutes. This means that the first flight flew out of Atlanta using the KAJIN route after it had been clear of adverse weather for 40 minutes. To visualize this, the data equal to that provided by the RAPT Evaluation Post-Event Analysis Tool (REPEAT) that also provides plots that integrate weather impacts and departures on the timeline under study. The PIG plot for the KAJIN route can be seen in Figure 4. The departure timeline indicates that KAJIN was used until weather impacted the route availability around 21:30. The PIG begins at 23:30, when the route is first free from weather. The first departure is at 24:10 (i.e., 00:10 the next day), 40 minutes after the route is clear. The time to first departure is highlighted with the purple box in Figure 4.

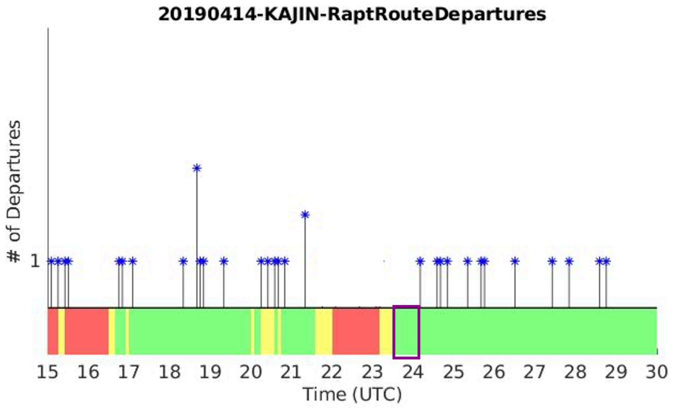

Figure 4. KAJIN Post-Impact Green (PIG) Time to First Departure (TFD) plot.

The sum of all the TFDs for each route for all of the weather days results in the number of minutes that routes were clear of weather impacts but were not used. This value can be used to estimate the potential additional departure opportunities across all the ATL routes in minutes.

D. Departure routes maximum throughput analysis

To convert minutes of opportunity to additional departures, a measure of each route's throughput (and hence capacity) needed to be identified. Because the usage of each route can be affected by many factors, this measurement was done using a parametric approach applied to historical data of actual usage of the routes. Ten clear weather days (no or minimal precipitations present during the day time) in 2019 were selected in ATL and the results were plotted for each adapted route. Figure 5 presents an example for the KAJIN route to the west of ATL. Maximum, median and 75th percentile throughput was used as a measure of the route capacity. To identify an upper bound of the route capacity, the maximum (red) and median (blue) throughput was calculated during the clear days. The box plots, including the 75th percentile, were instead calculated during 13 days in 2019 affected by weather. These 13 days were a subset of the 37 impacted days (see Section IV.A) during the entire convective season and were chosen using the same approach. The results in Section F will be presented using these values.

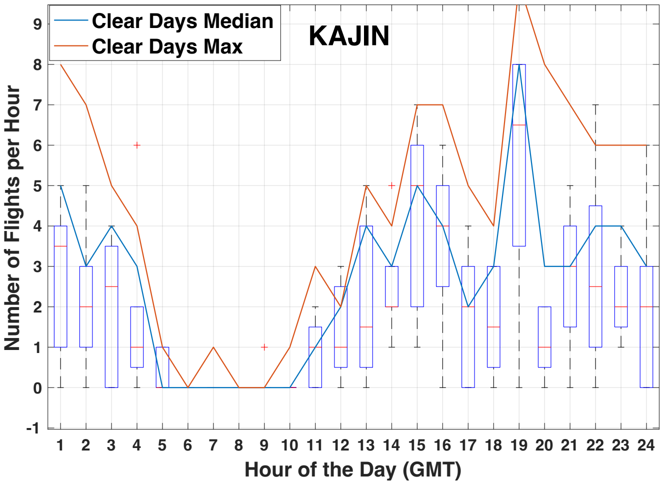

Figure 5. Observed hourly departure throughput for KAJIN route, median (blue line), maximum (red line) during clear days, and box plots during weather-impacted days.

E. Available demand using departure score analysis

To quantify if demand was available on the ground during the opportunity times identified, the hourly departure score recorded in the FAA ASPM database was used [11]. The departure score is defined as the percentage of time departures are greater than or equal to departure demand or the facility-set departure rate. The percentage is determined by dividing actual departures by the lesser of the departure demand or the departure rate. This is a proxy to identify periods when the airport is not able to process all of its departure demand. ATL operates at a very high level of departure score: in 2019 its average departure score was 96.4% (see red line in Figure 6).

In 2019, there were 20 days where the departure score was below 80% for more than 4 hours. The results will be presented in the next section using all the opportunities (regardless of departure score) and the opportunities during times when the departure score was below 90%.

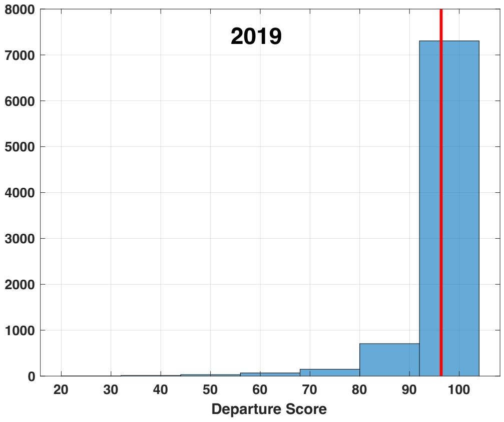

Figure 6. Departure score distribution in Atlanta in 2019.

F. *Results*

Following the methodology described above, it was possible to identify 37 days during the convective season of 2019 (April-September) with weather impacting ATL and departure scores lower than 90% indicating available demand on the ground. The time period opportunities were translated into a quantity of departure opportunities using the known route throughput during clear air. Results are presented parametrically using the maximum, 75th percentile and average route throughput in Figure 9.

During the 37 impacted days, 114 hours of opportunities (less than 3 per day) for all the departure routes were identified. Using the 75th percentile routes capacity, these time opportunities would have translated to 230 additional departures, or 6.2 departure per day on average (middle orange bar). Considering 75th percentile capacity and all days with Departure Score below 100, the opportunities would have been 445, or on average 12 per impacted day (middle blue bar).

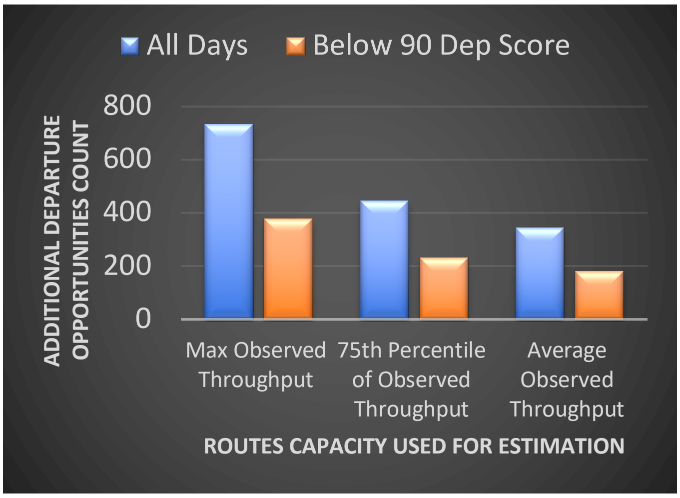

Figure 7. Potential additional departures in ATL in 2019.

If we consider the middle orange bar in Figure 9, 6.2 additional departures per weather-impacted day is a fairly small number and a testament that Atlanta operations run efficiently even under challenging conditions. Compared to the New York results published in [9], where 13.6 additional departure opportunities were identified for the three major airports, Atlanta's less rigid departure routes seems to adapt to weather impacts more efficiently.

V. GERMANY TOP-DOWN APPROACH

During the course of the project Met4ATM, which was funded in the context of Luftfahrtforschungsprogramm (LuFo) of the Federal Ministry for Economic Affairs and Climate Action (BMWK), Deutsche Flugsicherung (DFS) controllers located at MUC area control center were interviewed with regard to approach operations during convective weather impact. Temme at al. [15] provides a detailed insight, which is summarized here.

The runway system at Munich International Airport (MUC) consists of two independent runways 26R/26L, and respectively 08R/08L: see Figure 8.

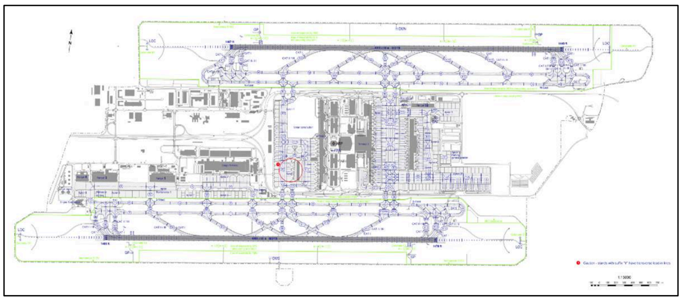

Figure 8. MUC airport layout (ICAO Aerodrome Chart, from DFS).

Approach operations in the Terminal Maneuvering Area (TMA) are divided into three functional sections: northern approach, southern approach and feeder, whereas the northern and southern approach positions are carried out by 2 controllers each (radar and coordinator). Both approach functions are responsible for the northern and southern runway respectively, whereas the transitions are formed by a path stretching area. Flying a transition from the Initial Approach Fix (IAF), downwind, base and final take about 12 minutes on average. Departures are generally routed under the transitions, depending on the crossing points between approach and departure trajectories to the runways. In most cases, the runways are operated in westerly direction (26L/26R). In the case where the arrival capacity of one runway is exceeded, compensation by dynamic traffic allocation to the other runway is carried out. This may happen several times throughout a day. In fact, during the day, runways are mainly used in mixed mode. This can be seen in Figure 9 where all the departures between 6:00 and 20:00 (local time) are plotted for June 10 2019, a day with weather impacts and at least one configuration change. During the night from 23:00 to 6:00, only one runway is open at a time, alternating in the daytime. In principle, there is a curfew, but due to special permits for exceptions, the airport is operated 24 hours.

During high demand rates, TMA airspace is separated into a “high” and a “low” airspace. In the higher airspace above FL95, aircraft are presorted, and then transferred to the downwind in the lower airspace. Northwest, northeast, and southeast, represent one sector, each with an individual metering fix, at which standard approach routes (STARs) are merged. Approaching traffic is typically presorted before reaching these merging points (metering fixes). This takes place on the upwind with double spacing of 12 nautical miles at FL120 and FL130, so that approach flows on the downwind can then be merged seamlessly and thus without delay with an average separation of 6 nautical miles. The approach controllers (“pickups”) guide aircraft to approximately ten nautical miles ahead of the IAF before transferring to the feeder. The Munich path stretching area is what is known as an open trombone. This means that the pilots are not allowed to turn onto the centerline on their own, even after the downwind has been completely flown, but must hold their course until they finally receive a turn-in clearance. This can be seen in Figure 12 where arrivals between 6:00 and 20:00 (local time) are plotted for June 10 2019. The downwind and the trombones together with their turning points are made visible as well as together with some flights holding patterns at the respective holding fixesbefore landing. As mentioned before, MUC airport was impacted by weather on this day.

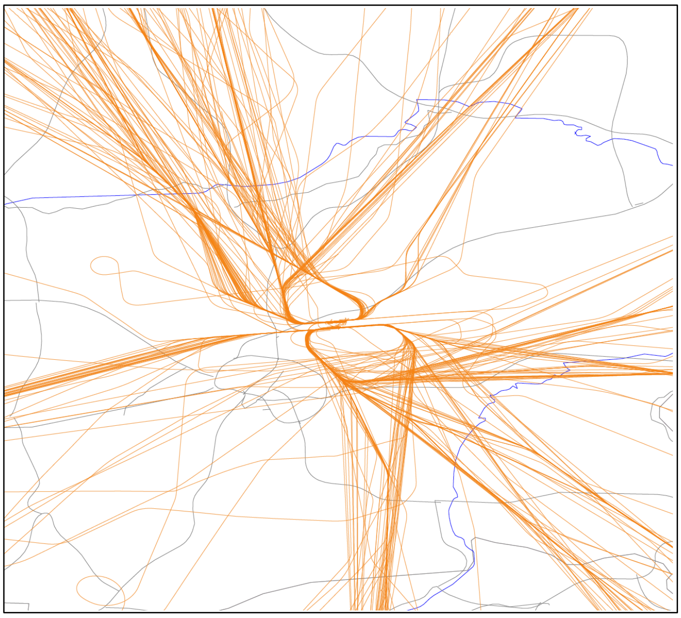

Figure 9. MUC departures on June 10 2019, 6:00-20:00 hours (dataset from OpenSky Network).

According to Temme at al. [15], extreme weather events at MUC and their predicted behavior should be known at least two hours in advance, so that appropriate action with active control measures can be taken. This also includes holding departures at other airports (similar to Ground Delay Programs in the US). Any events that occur at shorter notice can only be dealt with tactically. Wind forecasts are usually available to the controllers for a period of six hours. Meteorological information is provided by the German Weather Service (DWD). DWD meteorologists and supervising controllers confer twice a day for a comprehensive weather briefing. If convective weather is expected in one or more sectors, supervisors recommend opening overflow sectors. Nevertheless, sectors are controlled individually depending on the approach direction. Planners and coordinators do not usually look at forecasts beyond two hours in most weather situations. Information about the next fifteen minutes is of higher importance in terms of highly accurate weather forecasts for safety relevant decision-making.

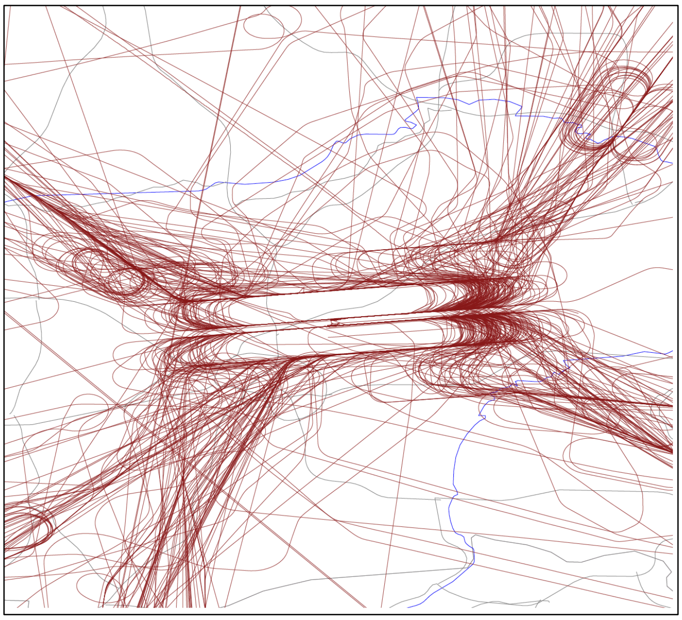

Figure 10. MUC arrivals on June 10 2019, 6:00-20:00 hours (dataset from OpenSky Network).

Thunderstorms very quickly lead to the interruption of flight operations at MUC, as handling is completely suspended if there is a risk of lightning. The rule is that if lightning strikes at a distance of less than three nautical miles from the airport, handling will be suspended by the traffic manager in the tower via an emergency system in order to avoid dangers for employees outside. Under these circumstances, the apron can become crowded.

If complexity increases, e.g., due to extreme weather conditions within the TMA, two feeder positions (Director Munich North/DMN and Director Munich South/DMS) are added, which coordinate both approach flows as independently as possible. This needs to be weighed with a potential increasing coordination effort between these two feeders. If complexity further increases due to convective activity, the runways can no longer be used independently. Under severely restricted visibility conditions (CAT III a/b), the runways are operated using one for take-off and one for landing operations. Up to three arrivals per hour are processed on the departure runway. Usually departures are being held on the ground under adverse weather conditions. Normally, about 42 movements can be accepted per runway but the capacity can decrease to 20 movements per hour under severe weather conditions. In these cases, TMA capacity is also decreased.

VI. MUNICH WEATHER DAYS ANALYSIS

The study presented in the previous section was focused on baselining the operations at MUC during convective weather. In this section, although data on the potential additional departure opportunities was not available for MUC, starting from the delay data presented in Section III.B, a deep dive into the weather impacts at the airport identified interesting weather case days.

The analysis presented in this section used the same EUROCONTROL database, but a subset of the categories shown in Figure 2 to drill down into MUC weather-related airport delays. Figure 11 provides monthly Air Traffic Flow Management (ATFM) airport delay values for 2019 by total delay minutes and daily averages for each month. ATFM delays are defined as delays imposed by the European Network Manager to balance demand and available capacity at major airports and within airspace which can be caused by weather. They are calculated as the difference between the estimated take-off time (ETOT) and calculated take-off time (CTOT) and represent the share of delays incurred as a consequence of network restrictions. Weather related monthly delay values are typically mainly driven by winter weather/icing conditions during the winter months (November to February) and convective activity during the summer months (June to August). During these months, July 2019 had the highest delay with about 13,000 minutes total and daily average of about 425 minutes.

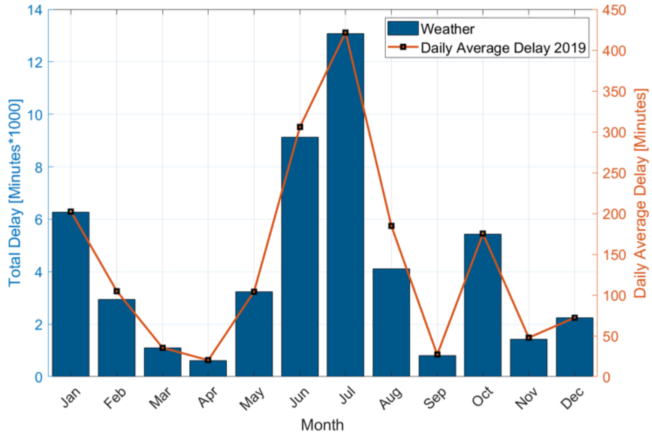

Figure 11. MUC ATFM airport delay evolution per month 2019. Data: EUROCONTROL CODA database.

In total, MUC had 59 days with weather impact in 2019 (vs 37 in ATL), based on the existence of weather-related ATFM delay (without any minimum threshold definition). Figure 12 shows absolute weather-related delay values for June to August 2019 on a daily basis, allowing to identify those days with a high potential for convective activity in the vicinity or directly over the airport.

Two days, July 1st and June 20th 2019, stand out with total delay values over 4,000 minutes. In order to evaluate weather impacts on these two days, Cb-global computations were carried out [17,18]. Cb-global is a fully automated thunderstorm tracking, monitoring and nowcasting tool developed by DLR. The detection and nowcasting of convective activity are based on spectral channel data from geostationary satellites. Four satellite channels are combined in order to identify three different development stages of the thunderstorm lifecycle: convective initiation, rapid growth, and mature. The performance of Cb-global has been verified by a comparison with lightning data over Europe and South Africa [16] and applied in various aviation case studies [17].

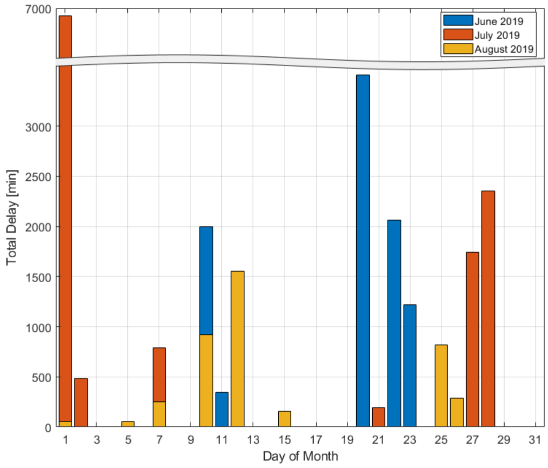

Figure 12. MUC ATFM daily delay (weather) Jun-Aug 2019. (data: EUROCONTROL CODA)

Figure 13 provides the convective situation in the nearby airspace around MUC on July 1st 2019 between 13:20 UTC and 14:20 UTC, which was the most impacted time period throughout the day. The airport position is indicated in the center in light blue text. Several mature convective cells (red polygons) are moving northeast through the terminal area. This implies a westerly operating direction of the airport runway system as described in Section V. Convective cells especially impact departure operations by blocking the departure routes of both runways. Even if no convective cell identified by Cb-global appears directly over the airport, convective activity including lighting is very likely to have had an impact on airport ground operations in this time period. Hence the very high number of delays shown in Figure 12 for this day.

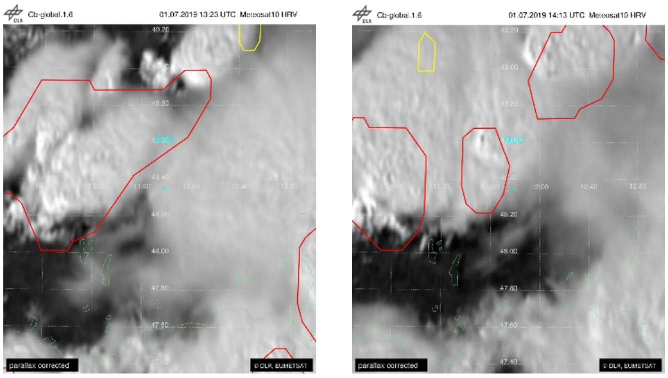

Figure 13. Cb-global visualization of convective activity within MUC TMA, July 1st 2019 13:20-14:20 UTC. Red polygons indicate mature convective cells, yellow polygons indicate convective cells in an early development stage.

Ground operations were also very likely interrupted on the 20th June 2019: see Figure 14. Also, on this day, mature and large convective cells (red polygons) were moving northeast through the terminal area with an impact on arrival and departure routes, whereas at around 15:00 UTC the airport was directly affected by convection. Total impact duration is about 3 hours. With an average of about 70 movements per hour (departure and arrival) on this day, over 200 movements have been directly impacted.

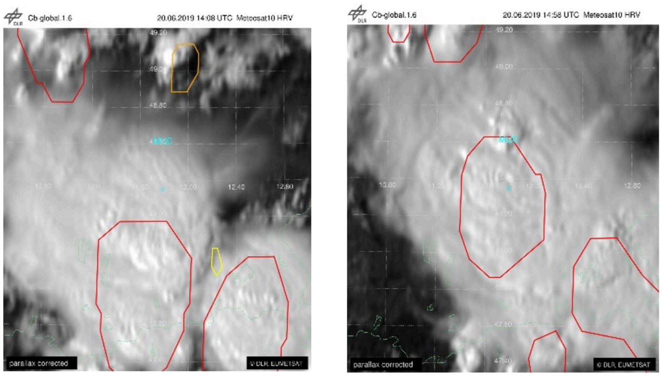

Figure 14. Cb-global visualization of convective activity within MUC TMA, June 20th 2019, 14:00-15:00 UTC. Red polygons indicate mature convective cells, orange polygons indicate convective cells in a solid development stage and yellow polygons indicate convective cells in an early development stage.

Similarly, to the analysis presented in Section IV for ATL, the analysis presented in this section helped to identify weather impacted days at MUC. Depending on the location and length of the convective weather events, higher number of delays were experienced by the airport. From the data presented in Figure 12 the July 1st event had a higher impact showing larger convective weather cells (in red) than during the June 20th event. This data also confirms the results of a previous study in MUC on the convective weather impacts presented in [18].

VII. COMPARISON OF APPROACHES

From the analyses presented in Sections IV, V and VI it is clear that different approaches are all valuable but provide different pros and cons. The data-rich and software-intensive analysis developed for ATL can really show the weather impacts on departure routes to the minute and help to identify potential additional operational benefit opportunities (with additional technologies provided to ATC). On the other hand, this approach is labor intensive and needs to be validated directly with operational subject-matter experts that are familiar with current operations at the facilities analyzed.

The MUC operational study presented in Section V, on the other hand, cannot provide a pool of additional opportunities and benefits. But it is important to baseline the operations and to understand how airports react during convective weather events. This was not provided by the ATL study. Moreover, the operational baselining can be used to start designing future operations to be more effective.

Similar to the study in ATL, the MUC weather days study presented in Section VI can help to identify days where impacts at the airport were present (high delays) and perhaps as a starting point to identify potential operational improvements.

From the ATL and MUC studies is also clear that convective weather has significant and similar impacts at both airports. Although the ATL study is focused on the convective weather season (March 1st to September 30th), while the MUC study focused on the entire year, a similar number of weather-impacted days was obtained: 59 days in MUC versus 37 in ATL.

An operational study like the MUC one performed in ATL could help to baseline what are the airport's reactions to convective weather events. It is interesting that ATL, although with more runways than MUC, has a similar east-west configuration. The weather in MUC seems also to move from south-west to north-east as in ATL. Therefore, some interesting lesson learned could be obtained by such a study. Similarly, it would be interesting to apply the ATL data-driven approach to MUC to identify weather impacts to the departure routes.

It also needs to be mentioned that the weather data itself for the ATL (CIWS/CoSPA) and MUC (Cb-global) studies were not compared in this paper in terms of resolution, update rate, and approach to create convective weather polygons. This would be very rich research for future work valuable for both ANSPs.

VIII. DISCUSSION, CONCLUSIONS AND NEXT STEPS

This paper was a first step at looking at similarities and differences in how major airports deal with convective weather impacts. Many aspects of the data presented in this work could inspire deeper dives in different areas. For example, the total number of weather delays in MUC and ATL in 2019 was not directly compared because the definitions of what a weather delay is might differ. From a percentage point of view (see Section III), it seems that in 2019 more than 50% of the departure delays in ATL were caused by weather but only 12.1% in MUC. This seems somehow unreasonable but it is probably caused by the classification issue.

As previously discussed, there is a fundamental difference in how airport capacities are set in US (VMC conditions) and Europe (IMC) as discussed in [3], making US airports more susceptible to weather delays, but the percentage difference seems too high. Lastly, even considering the IMC/VMC difference, ATL has plenty of runway capacity to process its daily schedule. The convective weather impacts, as shown in section IV, are also ascribable to the departure routes and airspace similarly to MUC. Therefore, a study on how to benchmark the delay classification would be very interesting.

Weather forecast models are key tools for ATC to predict and manage weather impacts, but the approach to translate this information into actionable ATC decisions is even more crucial. Comparing what type of decision-support-tools are used in the US and Germany would provide great benefit to the ATM community and also help to define technical requirements for these tools and how they might be effectively utilized in a harmonized way in different countries.

In the United States, the approach described in Section IV, is now being extended to airports in Florida. Moreover, the approach is being expanded to also capture the impact of weather on airspace capacity for arrivals. Florida airports and airspace are subject to frequent convective weather events and a recent increase in the demand to fly to this area has been causing more delays than in the past. Results from this approach will be presented in future publications.

Lastly, there are other ATM topics that would benefit from exchange of best practices between the US and Europe such as the one presented in this paper. Among the most relevant:

- How to manage operations at airports close to national borders such as MUC in a time-based metering environment. The limited time in controlled airspace might make the application of Trajectory-Based Operations (TBO) difficult. Although not in the US, a similar problem affects Toronto Airport in Canada.
- How to efficiently manage space launches with traditional air traffic. Recently the first space launch from European soil was performed in the United Kingdom and lessons-learned from the rapidly growing commercial space industry in the US could be applied to European space operations.
- Urban Air Mobility is a growing field and multiple applications, concepts and vehicles are being developed both in the United States and in Europe.

These topics should be investigated in future collaboration projects that could benefit from more streamlined information exchange mechanism.

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AUTHORS BIOGRAPHIES

Gabriele Enea is a Technical Staff in the Air Traffic Control Systems Group at MIT Lincoln Laboratory. He has received his laurea (BS + MS) in aeronautical engineering and his Ph.D. in transportation engineering both from the Universita' degli Studi di Palermo, Italy. He also received a Master of Science in transportation engineering from Virginia Tech, USA.

Alexander Lau is acting Head of the Department "Flight Operations Concepts" at DLR Institute of Air Transport, Hamburg, Germany. He received his diploma in Aeronautical Engineering from Berlin University of Technology and worked for DFS German Air Navigation Service Provider. He obtained his doctoral degree from Hamburg University of Technology.

Margita Pawlak is an Assistant Staff in the Air Traffic Control Systems Group at MIT Lincoln Laboratory. She has a B.S. in mathematics from the University of New Hampshire.

Tom Reynolds is the Leader of the Air Traffic Control Systems Group at MIT Lincoln Laboratory which develops advanced ATC technologies. He has a Ph.D. in Aerospace Systems from MIT. He has worked on the research staff at MIT and the University of Cambridge, and in industry at British Airways Engineering and the UK Defense Evaluation and Research Agency.

With over 25 years of experience at the FAA, **Mr. Dave Knorr** is the Division Manager for NextGen Systems Analysis and Modeling. Mr. Knorr is also co-chair of the NextGen Advisory Committee (NAC) Joint Analysis Team (JAT) with the Airline Industry. His previous experience includes being the FAA Senior Representative in Paris and the FAA Liaison to Germany's Air Traffic Organization. Mr. Knorr has co-authored more than 16 technical papers related to aviation performance and operational efficiency. He holds a BS in Mathematics and a Masters in Engineering Administration, both from Virginia Tech.

Martin Durbin is the Manager of the Operations Performance Assessment Branch of the FAA's Office of NextGen. While at the FAA he has supported post-operational implementation analysis and operational shortfall studies. Previously, he developed real-time scheduling tools for Walt Disney World, Virginia Concrete, and Rosetta Stone. He holds a B.S. from Murray State University in Engineering-Physics, an M.S. from George Mason University in Operations Research, and a Ph.D. from George Mason University in Information Systems.

Stefan Schwanke is working as a requirement engineer for aviation weather data and systems at DFS German Air Navigation Service Provider for four years. Since 2008 he was working at DFS R&D department participating in several projects with meteorological aspects. He studied Aeronautical Engineering at the universities Stuttgart, Toulouse and Munich and finished with a diploma degree in 2001 in the field of jet engine design.