Analysis of Weather-Driven Air Traffic Management Challenges for Major U.S. and European Airports

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***Abstract*—This paper develops a general framework for systematic comparison of weather-related air traffic management (ATM) challenges at major airports worldwide and applies it at specific facilities in the U.S. and Europe. Using meteorological and operational databases, we apply the proposed framework to objectively compare and contrast patterns that account for: (i) the types, severity and frequency of operationally challenging weather conditions such as convective storms, winds, ceiling and visibility and precipitation affecting airport operations; (ii) resulting weather-driven demand/capacity imbalance characteristics; and (iii) strategic and tactical ATM responses and resulting delay characteristics. Preliminary results indicate that U.S. airports experience a higher frequency of convective storms, leading to greater operational disruptions, while European airports are more affected by low visibility events, which play a larger role in performance metrics. The paper concludes with a summary of insights gained from the application of this framework and proposed future work to inform research and development efforts, promote best practices and enhance ATC harmonization.**

Keywords-weather, air traffic management.

I. Introduction

Adverse weather at airports and in en route airspace is a significant contributor to commercial aviation operational inefficiencies in both the U.S. and Europe, and its impact may increase as more frequent extreme weather occurs in association with climate change. Weather is the most common "off-nominal" scenario affecting aviation and can have severe effects on operations. While meteorological forecasting capabilities continue to improve, the accuracy needed to characterize impacts on critical individual airspace resources and estimate the associated capacity reduction on the multi-hour timescale required for optimized ATM continues to be challenging.

Delays caused by challenging weather conditions are more significant in the U.S. than in Europe. The most recent Federal Aviation Administration (FAA)/EUROCONTROL report [1] characterizing ATM operational performance in the two regions attributes 76% of delay in the U.S. to weather versus 29% in Europe. However, the summer of 2024 in Europe experienced particularly severe weather, leading to an anticipated rise in the proportion of weather-related issues. At present, at least four key differences between the U.S. and Europe likely account for the greater weather-related impact on operations in the U.S, as discussed below.

First, convective storms are much more prevalent in the U.S., particularly in the congested airspace near major airports along the east coast and at "hubs" in the Midwest and Southern U.S. A recent analysis of severe weather climatology in the U.S. and Europe [2] quantifies the much greater prevalence of severe weather in the U.S, indicating for example that the number of hours per year during which lightning occurs near the 4 highest-operations U.S. airports (Atlanta (ATL), Chicago O'Hare (ORD), Dallas Fort Worth (DFW) and Denver (DEN)) ranges from 40 to 65, whereas for the 4 most active airports in Europe (Amsterdam (AMS), Paris Charles De Gaulle (CDG), Frankfurt (FRA) and London Heathrow (LHR)) the corresponding range is 10 to 30. Thunderstorms are particularly disruptive to commercial aviation as their impacts can be extreme (e.g., airport shut-downs, reduction in en route capacity) and they are challenging to forecast with the necessary temporal and spatial accuracy. In Europe, cool-season phenomena such as low visibility and winter precipitation may have a greater annual impact on aviation operations than thunderstorms [3][4], although long-term changes indicate that winter precipitation is becoming less frequent while the number of thunderstorms is increasing, particularly over northern, central and south-central Europe.

Second, significantly more conservative scheduling paradigms are used in Europe to reduce the occurrence of demand/capacity imbalances. In general, airport arrival schedules at European airports are based on Instrument Flight Rules (IFR) capacity estimates rather than Visual Flight Rules (VFR)[1] capacity as is the case in the U.S. Strategic planning, often months in advance, is used to set airport arrival rates based on demand negotiations with air carriers and expected capacity constraints. In the U.S., only 3 airports have schedule limitations, whereas in Europe almost all major facilities are regulated through an airport scheduling process.

Third, while both U.S. and European air navigation service providers (ANSPs) limit demand during adverse weather

[1] In this paper IFR and VFR will be used in place of Instrument Meteorological Conditions (IMC) and Visual Meteorological Conditions (VMC).

conditions by delaying departures at the origin airports, the U.S. system makes much greater use of tactical coping methods such as "miles (or minutes) in trail" in en route airspace, airborne re-routes, holding patterns, and vectoring in congested terminal airspace. These procedures likely increase the number of operations that can be achieved during adverse weather but may also contribute to greater average delay per scheduled flight.

Finally, the aviation system in the U.S. has more hub-and-spoke connections for passenger transport than the European system. Some of the airports that major U.S. carriers use as hubs are regularly subject to adverse weather conditions. For example, Chicago O'Hare (ORD) and Denver International (DEN), both experience snowstorms and severe thunderstorms which often disrupt flight schedules. Major disruptions at a hub often propagate and impact the whole air transport network.

To date there has not been a quantitative analysis showing how these differences in adverse weather exposure and ATM paradigms explain the substantial differences in delay attributed to weather in Europe relative to the U.S., and how weather-related delay in both regions may evolve as demand - and potentially weather severity - increase in the future. This paper seeks to address that shortfall by establishing a consistent framework for assessing delays at major airports in the U.S. and Europe using established meteorological and aviation-operations databases. Our analysis accounts for: (i) "climatological" exposure to weather phenomena that limit capacity at airports or their associated en route/departure/arrival airspace; (ii) airport demand profiles in relation to their estimated peak capacity during various meteorological conditions; (iii) current ATM procedures at the different airports which may substantially affect operational efficiency; and (iv) statistics characterizing delay metrics at each airport. We believe that this framework provides an important starting point for assessing current and future ATM performance scenarios worldwide, and for establishing R&D priorities that may mitigate the impact of adverse weather on ATM performance.

The next section summarizes relevant analyses by both European and U.S. researchers of weather-related ATM inefficiencies. With only a few exceptions, these studies have been confined to either the U.S. or the European system, and none have used consistent methodologies in comparing weather-related delay characteristics across the two systems. In section III, we describe our novel analysis framework incorporating geographic-specific weather exposure estimates and operations data to quantify the impact of current Traffic Management Initiatives (regulation) strategies and tactical procedures in addressing weather impacts on operations. Section IV describes the European and U.S. meteorological and ATM operations databases used in developing our framework. Methods for reconciling differences or omissions in the available data are discussed. Section V presents example results from application of the proposed framework and databases to illustrate some of the insights that can be gained, some of which are detailed in Section VI. Section VII summarizes our findings and suggests future directions.

II. Literature Review

Weather significantly impacts the air transport system. Although the specific weather phenomena and resulting disruptions vary between the United States and Europe, they are substantial in both regions. A significant portion of the literature reports on research conducted in the United States. This focus may be indicative of the greater potential for weather-related disturbance in the United States or the better availability of data for research purposes.

According to the FAA [5], weather is responsible for three-quarters of delays exceeding 15 minutes within the National Airspace System (NAS) from 2017 to 2022. New York, Chicago, and San Francisco experienced the largest weather-related delays. In contrast, the EUROCONTROL Central Office of Delay Analysis (CODA) reports [6] that approximately half of the delays in the European aviation system are "reactionary delays", with "airline causes" being the second most common reason for delays. The FAA does not report reactionary delays. The root cause of the reactionary delay in the CODA data may be weather-related during a previous rotation, which makes direct comparisons of weather impacts between the U.S. and Europe challenging. Additionally, as previously discussed a key difference is that, unlike in Europe, few airports in the U.S. are subject to arrival-flow regulation, making them more susceptible to demand-capacity imbalances. This issue, which affects normal operating conditions, is significantly exacerbated during disturbances when arrival capacity is greatly reduced.

Buxi and Hansen [7] developed a static probabilistic weather forecast based on available weather predictions. They found that comparing the capacity forecast to the realized historical capacities illustrated significant benefits of probabilistic capacity profiles over deterministic profiles. Enea et al. [8] contrasted operations at a U.S. airport (Atlanta (ATL)) and a European airport (Munich (MUC)), both of which experience significant convective weather. A direct comparison was not possible due to different metrics and definitions; for example, almost 50% of delays at Munich airport were due to "Airline" causes according to the IATA delay codes. However, this category might well include weather impacts on airline operations earlier in the day. It is, nevertheless, evident that operations at both airports are heavily impacted by convective weather. There are opportunities to mitigate this impact by identifying potential for additional movements. A previous study by Odoni et al. [9] benchmarked operations at New York Newark (EWR) and Germany's Frankfurt Airport (FRA) with a view to their weather dependence. Despite a higher number of operations (in 2007), Frankfurt was found to be less vulnerable to weather disturbances. Unlike Frankfurt, which operates under regulated conditions and bases its capacity on typical Instrument Flight Rules (IFR) conditions, Newark, like many U.S. airports, is a non-regulated airport with capacity based on Visual Flight Rules (VFR). This distinction was identified as a potential factor contributing to Newark's higher sensitivity to weather, particularly convective weather.

An analysis of weather-related delay at European airports was reported by Schultz et al. in [10] who analyzed METAR reports and aggregated the different weather conditions to a composite score, the ATM Airport Performance (ATMAP) weather score, which considers the severity of different phenomena. Munich (MUC) and Oslo (OSL) were the airports most affected by significant weather events in Europe. Strong correlations were reported between the aggregate METAR score and indicators such as cancellations and arrival/departure delay, permitting airports to proactively estimate and mitigate capacity impacts of projected weather phenomena directly from METAR reports. In [11], Klein et al. conducted a related study in the U.S., where they developed the NAS Weather Index (NWI) which extends an existing metric assessing the impact of weather on both airport and terminal air traffic. Unlike previous models that treated the effect of weather as linear, NWI incorporates a queuing model to more accurately represent the non-linear nature of weather-related disruptions. Sánchez et al. [12], proposed the use of Machine Learning (ML) to enhance the European Network Operations Plan through analysis of historical flight data. They developed a probabilistic weather prediction module connected to a hotspot and capacity identification module. A visualization tool was used to display both the weather impact and anticipated capacity reductions to the flow manager. Dalmau et al [13] modeled the airport peak service rate during adverse weather effects. The airport peak service rate was used as a proxy for airport capacity estimated from historic data as a function of weather (derived from METAR data) and runway configuration. Peak service rate was then estimated using Gradient Boosting Decision Trees. Noteworthy is that the model was trained across a large set of European airports, not for individual airports, which allows for generalizability.

Moreover, weather phenomena, including those causing disruptions to the aviation system, may change due to global warming. Burbidge [14] analyzed current predictions regarding the occurrence and intensity of European meteorological phenomena. The analysis concluded that, on a European scale, disruptions caused by storms might decrease slightly. Conversely, flooding due to sea level rise, and related airport disruptions, might increase significantly because many European airports are in coastal and low-elevation areas. A similar and very detailed analysis performed by EASA [15] concluded that the frequency and intensity of severe thunderstorms is likely to increase in the United States while for Europe trends are less clear and geographically nuanced.

III. Framework to Analyze Weather/ATM Impacts

Figure 1 presents a general framework for systematic comparison of weather-related air traffic management challenges. On the left side are the key inputs of airport selection, together with weather, traffic, ATM & operational outcome databases as described in Section IV. These feed the various assessment steps focusing on weather, demand/capacity and ATM response.

In the *weather assessment* step, the major weather types, their severity and frequency are categorized for the selected airports. For example, this could include the number of events and/or hours per year where operationally significant weather (such as strong winds, convection/lightning, ceiling/visibility and snow/ice) exists at the airport based on the weather data archives available.

In the *demand/capacity assessment* step, the outputs from the weather assessment are used to determine weather-impacted capacity at the target airports. The translation of weather-to-capacity impacts is non-trivial, but several techniques have been developed to perform this step, such as assessing weather impacts on Airport Arrival Rate (AAR) and the "permeability" of the airspace around an airport. For example, Wang and Zhang [16], Provan et al. [17], DeLaura et al. [18] and Cox and Kochenderfer [19] describe methods for predicting AAR using observed or modeled meteorological parameters. Song et al. [20] and Cho et al. [21] describe methods for quantifying en route sector capacity reductions caused by convective weather. Such reductions may significantly impact airport operations by constraining arrival and/or departure capacity. Many metrics can be used to define demand characteristics, such as airport aggregate demand levels, schedule (e.g., spread throughout the day or in banks) and aircraft mix. By understanding both

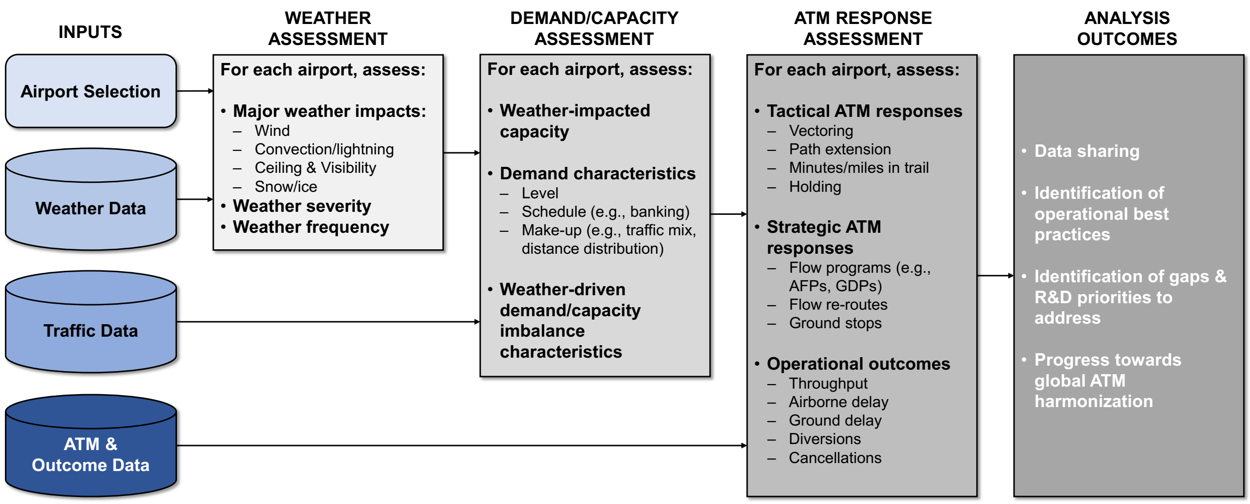

Figure 1. Framework to analyze impacts of weather-driven ATM impacts.

weather-impacted capacity and demand characteristics, an assessment can be made of the potential for a demand/capacity imbalance, which in turn determines whether ATM interventions are necessary to manage demand. For example, an airport with severe weather-driven capacity constraints but low demand levels or vice-versa will not need significant ATM involvement. But an airport which routinely operates with demand close to its clear weather capacity will have little tolerance for disruptions due to weather and therefore may regularly need ATM intervention.

The frequency, level and effectiveness of the interventions needed are characterized in the *ATM response assessment* step using the operational outcome data archives. This could include quantifying levels (absolute number and frequency) of tactical (short time horizon, 0-2 hours) ATM responses such as ground stops, vectoring, path stretch, miles/minutes in trail and/or holding. In addition, strategic (longer time horizon, 2+ hours) ATM responses such as airspace/ground flow programs and re-routes can be characterized. A subset of these is presented in this study. Then, the operational outcomes in terms of throughput, delay (ground and air), diversions and cancellations can be characterized. For example, an airport with severe weather-impacted demand/capacity constraints but an efficient and flexible ATM response environment is likely to have much less delay and/or diversions/cancellations than an airport where ATM response is more constrained or less efficient.

Finally, the *analysis outcomes* step is where the findings from the previous steps at a set of interesting candidate airports are synthesized and compared, allowing identification of operational best practices, gaps or opportunities to inform R&D priorities leading to a more efficient and globally harmonized ATM system.

IV. Databases Available for Comparison of Weather Delays between U.S. & Europe

Distinct but analogous databases exist in the U.S. and Europe for assessing the relative exposure of specific airports to adverse weather phenomena and the associated impacts on operational performance.

Convective storm impacts must be characterized not only at or near the airports of interest, but in the major flow corridors which feed arrivals to, and accept departures from, the airport. In the U.S., the occurrence of major storms and other significant weather phenomena are logged in the National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Information (NCEI) Storm Events database (https://www.ncdc.noaa.gov/stormevents/). This captures severe weather events on a national scale from 1950 to 2024, but may not include smaller scale thunderstorms that can significantly impact aviation without crossing the threshold for major impact on the broader public. Fine-scale observations of thunderstorms from the U.S. national Doppler weather radar network (NEXRAD) are also archived by NCEI (https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00708/html) and are available from the mid-1990s to the present. These are invaluable in understanding storm impacts on specific days but may be cumbersome and labor-intensive for use in more climatological analysis of airport weather exposure. Finally, National Lightning Detection Network (NLDN) archives [22] are likewise available from the mid-1990s to the present and can be efficiently processed to characterize thunderstorm occurrence climatologically in any U.S. airspace relevant to our study.

Similarly, the European Severe Weather Database (ESWD) archives significant convective weather events from approximately 1980 until the present [23]. As noted above, this may not capture some smaller scale storms that impact aviation operations. In Europe, the national weather services are responsible for weather radar observations in their own countries but cooperate through the European Meteorological Services Network (EUMETNET) to provide real time and archived continental scale observations through the Operational Program for Exchange of Weather Radar Information (OPERA) [24]. Since 2011, the OPERA Data Center (ODC) has created and archived Pan-European radar composites every 15 minutes which provide a long time-series of weather radar data for evaluation of storm impacts on aviation. As in the U.S., the European Arrival Time Difference lightning detection network (ATDnet) [25] provides an alternate, perhaps more efficient method for analyzing thunderstorm occurrence throughout European airspace.

Local weather conditions at airports in both the U.S. and Europe are archived via Meteorological Aviation Routine Weather Reports [26]. These provide information on wind, visibility, precipitation, cloud cover, temperature and pressure, and document significant phenomena such as thunderstorms at the airport or ice impacts on runways. EUROCONTROL [27] describes the ATM Airport Performance (ATMAP) weather metric - derived from METARS - which Schultz et al. [10] show correlates strongly with associated delay and cancellation metrics. Direct meteorological observations at airports in the U.S. and Europe are archived by NCEI in the Global Hourly Integrated Surface Database (ISD, https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database). Archived parameters include wind speed and direction, wind gust, temperature, dew point, cloud data, sea level pressure, altimeter setting, station pressure, present weather, visibility, precipitation amounts for various time periods, snow depth, and various other elements as observed by each station. Finally, NLDN or ATDnet lightning data can of course be used to document the occurrence of thunderstorms at airports.

In terms of operational outcomes, the FAA Aviation System Performance Metrics (ASPM) database [28] documents operational performance at essentially all mid- and large-sized airports in the U.S. and includes all IFR and some VFR flights. ASPM metrics are derived from the FAA's real-time Traffic Flow Management System (TFMS) and operational and delay data from airlines. Metrics on individual flight performance include scheduled and actual departure/arrival times and Gate Out, Wheels Off, Wheels On and Gate In (OOOI) times. Delay data can be derived from the Operational Network (OPSNET) and were used to calculate delay in this paper. The data are only available for flights delayed by 15 minutes or more. Individual flight level data is available for flights delayed due to the following Traffic Management Initiatives (TMIs): Ground Delay Programs (GDP), Ground Stops (GS), Airspace Flow Programs (AFP) and Collaborative Trajectory Options Programs (CTOP). These delays are reported using automation at the Air Traffic Control System Command Center (ATCSCC). Flights delayed due to other TMIs, which include Severe Weather Avoidance Plan (SWAP), Miles-In-Trail (MIT), Metering, and Departure/En-Route/Arrival Spacing Programs (DSP/ESP/ASP), are manually reported by facilities from where the aircraft departs. A portion of these other TMI delays do not have a destination airport because they are recorded manually by the departure facility as a group of delayed flights. ASPM reports also provide data on airport weather, runway configuration, and airport arrival and departure rates. This combination of flight and airport information provides a robust picture of air traffic activity for these airports and air carriers.

In Europe, performance data are derived from the Enhanced Tactical Flow Management System (ETFMS) of the European Network Manager and likewise utilize airline performance reports. The EUROCONTROL Network Manager Operation Center (NMOC) and the Central Office for Delay Analysis (CODA) collect these data and publish several performance metrics [6]. As in the U.S, key information relevant to our analysis are the "regulations" (i.e., TMIs) imposed in response to weather impacts on operations. These regulations are defined by the reference location to which they apply (e.g., a specific airport or airspace sector), the period during which they are in effect, and the entry rate, which specifies how many flights can enter that location per hour.

V. Results

As an example of how the framework in Figure 1 can be applied, we selected four airport-pairs in the U.S. and Europe where data indicate analogous weather challenges exist and assessed operational impacts and mitigations.

A. Airports Selection

We downloaded all European ATFM regulations due to weather from 1 January 2021 to 30 June 2024 with the reference location being an aerodrome. We then identified *keywords* like "visibility", "fog", "thunderstorms", etc. from the textual remarks written by the flow managers that activated the regulations. For example, a regulation with a text entry "low *visibility* at RWY23" would be assigned to the low visibility theme. The four defined themes were (1) low visibility, (2) thunderstorms, (3) strong winds and (4) snow. For each theme, we computed the airport associated with the most ATFM regulations, yielding the following results: Zurich (ZRH) for winds; Frankfurt (FRA) or Munich (MUC) for thunderstorms; Oslo (OSL) for snow/ice; and Porto (OPO) for visibility.

A similar analysis of ASPM Ground Delay and Ground Stop programs over the same period resulted in the selection of the following U.S. airports for further analysis: the New York airports LaGuardia (LGA) and Newark (EWR) for winds; Orlando (MCO) for thunderstorms, Chicago (ORD) for snow/ice; and San Francisco (SFO) for ceiling/visibility.

B. Weather Assessment

Figure 2 compares the mean annual number of lightning hours across the U.S. and Europe using consistent re-analysis methodology over multiyear intervals. The frequency of lightning at Orlando (MCO) is associated with high values of Convective Available Potential Energy (CAPE) and sea breeze front forcing over the Florida peninsula. Airport and terminal-airspace disruptions (e.g., suspended ramp operations, possible windshear and/or extreme precipitation on runways, blocked arrival and departure transition areas) combine with network related delays caused by thunderstorms affecting the primary routes to and from Florida along the U.S. east coast.

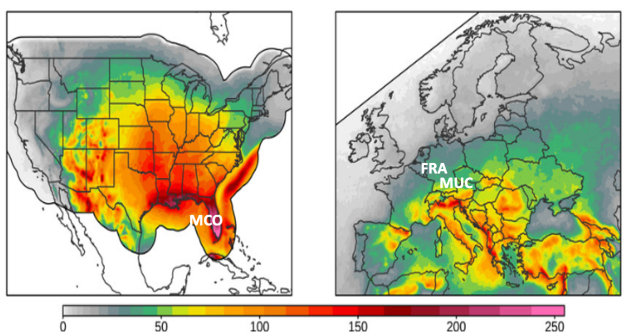

Figure 2. Mean annual number of lightning hrs across the U.S. & EU [3].

In contrast, the local occurrence of lightning at Frankfurt (FRA) and Munich (MUC) is much lower, suggesting that network impacts, particularly affecting routes from the south are the major contributors to convection-related delays at these airports.

Exposure to low ceiling and visibility, and to winter precipitation (snow, freezing rain, ice pellets) is comparable between the selected U.S. and European airports. Chicago (ORD) experiences snow-ice conditions during approximately 360 hrs/year compared to 280 hrs/year at Oslo (OSL) [2]. San Francisco (SFO) is impacted by ceiling less than 1000 feet for about 2100 hrs/year whereas Taszarek et al. [3] report that Porto (OFO) experiences 520 hrs/year of ceiling less than 200 feet, a significantly more stringent threshold.

We have not yet estimated quantitatively the yearly exposure to adverse winds at the New York City airports (LGA, EWR) and at Zurich (ZRH) as this requires both analysis of local meteorological station data and estimates of winds aloft, but our informal conversations with ATC facilities indicates this is a major challenge for them. Surface wind speed and direction affect airport acceptance rate by constraining runway configurations and/or requiring increased separation on final approach. Significant changes in wind speed and direction aloft can also reduce the efficiency of Trajectory-Based Operations.

C. Demand/Capacity Assessment

To quantify the demand/capacity ratio for each of the U.S. airports, the ASPM database mentioned above was used with data from January 2023 to July 2024. This period was chosen to capture recent performance not impacted by the effect of the pandemic, especially for the traffic demand. The metric of choice was the hourly percentage of capacity utilized defined as:

$$\frac{Arrivals+Departures}{Airport\ Arrval\ Rate\ (AAR)+Airport\ Departure\ Rate\ (ADR)}$$

For the chosen period, the data were divided by Visual Meteorological Conditions/Flight Rule (VFR) and Instrumental Meteorological Condition/Flight Rule (IFR). Figure 3 shows boxplots of the metric with first quartile, median (middle of the box) and third quartile plus outliers. From Figure 3, it is noticeable that the New York airports operate much closer to their hourly capacity compared to all the other airports in VFR. This difference is less significant in IFR. Orlando (MCO) is the airport with the most excess hourly capacity of the sample.

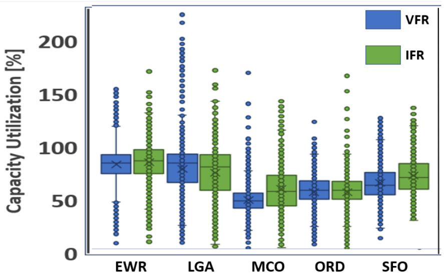

Figure 3. Hourly capacity utilization distributions during IFR and VFR conditions at selected U.S. airports.

In IFR, airports generally operate closer to their hourly capacity, this is understandable given that when a GDP is in place (more common in IFR conditions), the hourly capacity (i.e., AAR) is set as a control mechanism and demand is reduced to meet that as closely as possible. Not surprisingly, EWR, which has the highest number of GDPs, is the highest with a median of 82%, followed by LGA 72%. SFO is close to LGA with a median capacity utilization of 69.5%. MCO and ORD medians are slightly above 50%. These two airports are in fact the two with the lowest number of GDPs (see Figure 6). In VFR, considered here a proxy for fair weather conditions, airports operate at lower levels of capacity utilization. EWR is the highest with 81% median, consistent with IFR conditions. LGA's hourly capacity utilization median is 76%, SFO median is 62% while ORD is 53% and MCO is below 50%.

For European airports, the same formula used for U.S. airports was applied, but due to data limitations, global capacity (i.e., the number of hourly operations – departures and arrivals - the airport can handle) was used in the denominator. Therefore, this metric could underestimate the capacity usage compared to the U.S. metric. The global capacity for each airport was sourced from the publicly accessible "Airport Corner" (https://ext.eurocontrol.int/airport_corner_public/), which provides capacity data for various runway configurations. In cases where airports had multiple global capacities for different configurations, the highest capacity was used in this assessment.

The corresponding analysis for European airports during the same period (see Figure 4) shows the hourly capacity utilization in VFR and IFR, but also in Low IFR (LIFR) and Marginal VFR (MVFR). In contrast to the U.S. results, a decrease in capacity utilization during IFR is observed. We attribute this to the different airport scheduling paradigms in the U.S. and Europe. In the U.S., the denominator in the above equation decreases more than the numerator during IFR, whereas in Europe airport acceptance rates (capacity) are based on IFR capabilities and thus the denominator remains approximately constant while the numerator (demand) decreases.

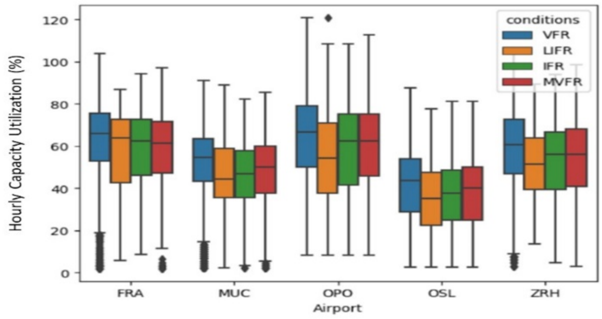

Figure 4. Hourly capacity utilization distributions during various conditions at selected European airports.

Among the sample of European airports, OPO operates closest to its hourly capacity in all meteorological conditions. In every condition, the median capacity utilization is above 60% at OPO. Lowest capacity utilization is observed at OSL, where in all weather conditions, the median is less than 50%. This is probably caused by a lack of demand for most of the day and by the general under estimation given by the European metric used.

D. ATM Response Assessment

To mitigate the imbalances that occur because of weather events, in the United States, the primary control mechanisms are Ground Delay Programs (GDP), Ground Stops (GS) and Airspace Flow Programs (AFPs). When a GDP is implemented at an airport, its hourly AAR is reduced and any scheduled flight that exceeds that rate is assigned a delay in the form of an Expected Departure Clearance Time (EDCT). A similar mechanism is applied when an AFP is implemented where an hourly acceptance rate is applied to flights entering a certain region of airspace. Lastly, a GS is usually implemented for short period of times when any flight arriving at the airport not yet in the air, is assigned an EDCT. For the selected airports in the period of January 2023 to July 2024, the results are presented in Figure 5.

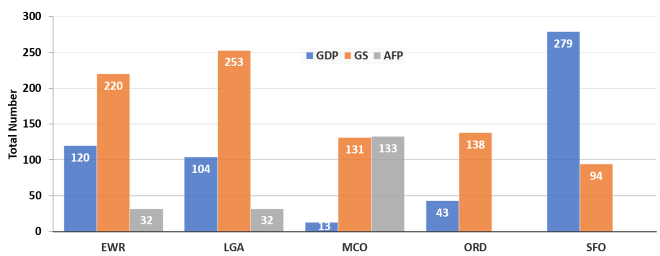

Figure 5. TMIs at U.S. airports of interest (Jan 2023 – July 2024).

First, it needs to be mentioned that SFO was undergoing a runway renovation project during the analysis period, therefore the abnormally high number of GDPs. EWR is the second with 120 GDP programs in the period analyzed. LGA had the highest number of Ground Stops (GS), which are the most tactical TMI of the three presented here. AFPs are not airport-specific, so the set typically used for North East airports were used for LGA and EWR that present therefore the same number of 32. This is significantly lower than the 133 that are attributed to MCO in the Jacksonville Center (ZJX) airspace. Obviously, the AFPs in ZJX are applied to mitigate the demand to all the airports in Florida, which have seen an impressive increase in demand since the end of the pandemic. Coupled with staffing challenges this has led to recent severe demand/capacity issues. On the other hand, MCO had only 13 GDPs but 131 GSs in the same period. These are usually short-lived and are used to suppress the demand quickly. SFO and ORD have no AFPs used to manage the airspace demand feeding them.

In Europe, when anticipated air traffic demand exceeds an airport's forecasted capacity, air traffic flow management (ATFM) regulations are often employed by flow managers to manage the imbalance. Flights affected by one or more of these regulations are assigned ground (ATFM) delays, determined on a first-planned, first-served basis through the Computer-Assisted Slot Allocation (CASA) system. This ensures that the maximum allowable entry rate (similar to the AAR)—measured in arrivals per hour—at the regulated airport is not exceeded during the designated time frame. ATFM regulations can be focused on specific airports or airspace resources. Therefore, the corresponding analysis for the same January 2023 to July 2024 period (see Figure 6) at selected European airports shows the number of regulations, corresponding to the total of the U.S. TMIs. It is seen that the total number of regulations is lower than the sum of the TMIs shown in Figure 5 for the U.S. airports, indicating less need for ATM interventions in Europe. It is seen that Oslo (OSL) experiences the fewest regulations during the period studied, which correlates with its lower overall capacity utilization. This suggests that OSL operates under fewer capacity constraints, allowing for smoother traffic flows even during adverse weather conditions.

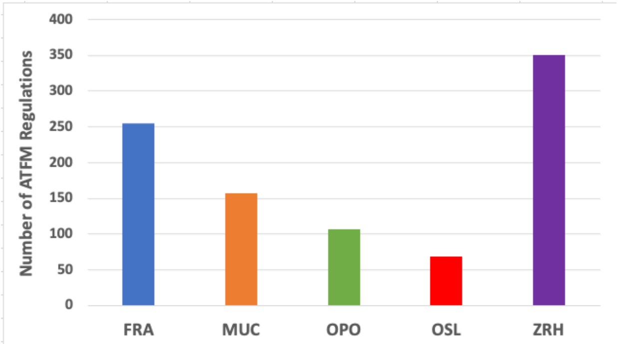

Figure 6. ATFM regulations at selected European airports (Jan 2023 – July 2024).

In contrast, Zurich (ZRH) stands out among the European airports analyzed, with the highest number of ATFM regulations applied. This can be attributed to the airport's susceptibility to challenging wind and low visibility conditions, which necessitate frequent ATFM interventions to manage operational disruptions. Frankfurt (FRA) and Munich (MUC) follow ZRH in terms of the total number of ATFM regulations, with both airports being significantly impacted by convective weather, particularly during the summer months. Such weather patterns, including thunderstorms and severe turbulence, often disrupt normal operations and lead to a higher frequency of regulations.

E. Operational Outcomes

To quantify the operational outcomes induced by the ATM responses at the U.S. airports analyzed, two metrics are presented here, both related to flights with Expected Departure Clearance Times (EDCTs). A flight is assigned an EDCT if it is part of a TMI such as GDP, AFP, GS, Time-Based Metering, etc. Therefore, the percentage of arrivals with an EDCT and the average EDCT delay for each aircraft with an EDCT greater than zero, are good metrics of the delays imposed by the ATM responses presented in Section V.D, during the same period. The results are presented in Figure 7. In the beginning of the period analyzed, LGA had the highest percentage of arrivals with EDCTs around 20% in January and February 2023 and a high average delay around 40 minutes per flight with an EDCT. The average delay at ORD reached more than 70 minutes in March and April 2023. LGA presented high average delays in June and July 2023 probably caused by the effects of summer convective weather in New York. MCO experienced very low percentage of arrivals with EDCTs across the entire period, with a maximum of 15.5% in March 2024. Nonetheless in April 2024 flights delayed to MCO had an average of more than 60 minutes of delays, although it was a very low percentage of 3.9% of the overall flights. SFO shows very high percentages of flights with EDCTs towards the end of the period analyzed. This, as explained before, was due to a runway closure. Up to 60% of flights arriving into SFO had an EDCT delay in March, April and May 2024. Nonetheless, the average delay per flight with an EDCT was around 30 minutes during the same three months. During the same period, ORD was showing very low percentages of overall arrivals with EDCTs (max of 9% in May 2024) but those flights that were delayed had an average EDCT of more than 60 minutes. In general, the lowest percentages of overall delayed flights are observed during the winter months, while the months of June and July are usually the worst for all airports. ORD shows some peaks in average EDCT delays in the winter months of January and February, explainable by the high impact of snowstorm events.

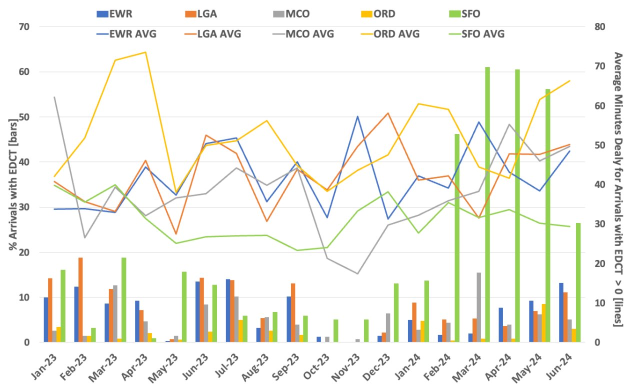

Figure 7. EDCT delays at U.S. airports (bars = %, lines = minutes)

Due to data differences, it was challenging to calculate the exact same metrics, so for the European airports' metric of impact, the total amount of delays imposed by a regulation at each airport was used. The results are presented in Figure 8 for the calendar year 2024 (i.e., not the same period as Figure 6). Even if FRA has a lower number of total regulations (roughly 250 versus 350 at ZRH), it has experienced more total delays than ZRH (more than 90,000 minutes vs roughly 75,000 minutes at ZRH). This could be caused by the higher number of flights included in each FRA regulation and on the duration of each regulation at the two airports. The rest of the airports show a similar trend to the number of regulations: MUC roughly 40,000 minutes, OPO roughly 30,000 and OSL the least amount with less than 40,000 minutes of delay. This is probably caused by the lowest number of flights at OSL airport.

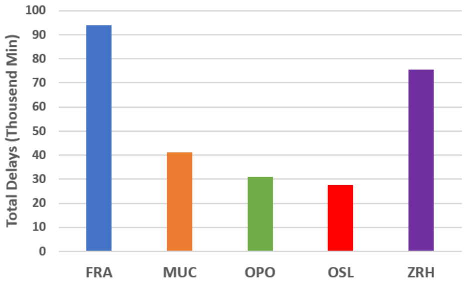

Figure 8. Total delays imposed by regulations at European airports (calendar year 2024).

VI. Discussion of Analysis Outcomes

The final step of the analysis framework presented in Figure 1 is to discern insights and lessons-learned from its application. The preliminary evaluation of airport weather exposure and operational impacts in Section V illustrates how our analysis framework can provide a systematic assessment of weather/ ATM impacts in the U.S. and Europe. We assess the exposure of corresponding airports to various adverse weather phenomena and quantify the impacts on operations. We show, for example, that airport capacity scheduling differences (VFR in U.S., IFR in Europe) result in opposite behaviors relative to the demand/capacity ratios observed during "clear" and "adverse" weather conditions. We compare ATM demand management responses and the resulting delay outcomes to show how adverse weather exposure and airport demand/capacity profiles affect performance. Several factors complicate the comparison of weather impacts between the United States and Europe. The type and intensity of weather phenomena differ as noted above. The fact that the majority of delays in the U.S. are related to weather could be at least partially due to a system architecture that is more sensitive to disturbances. The approach to determining airport capacity varies significantly. While few U.S. airports are schedule-constrained, this is the norm in Europe. The methods for balancing enroute demand and capacity also differ. In Europe, the Network Manager adopts a proactive flow management approach, whereas in the U.S., Traffic Management Initiatives are somewhat more reactive once system disturbances are observed. Lastly, delays are not categorized in the same way in U.S. and Europe, nonetheless, the two metrics presented in Section V, EDCT delays and regulations delays, are the closest to a one-to-one comparison available today, given that they are a measure of the total delays imposed by a specific ATM response.

Key opportunities from such as a systematic assessment between the U.S. and Europe are to identify (1) where there are best practices being used in one region which could be beneficial if adapted for use in the other, and (2) where gaps highlighted in the assessment can be addressed to benefit both regions (and beyond). Some preliminary thoughts in these areas based on this initial assessment which may warrant further study include:

- *Weather sensing & forecasting technology opportunities:* the U.S. system has some advantages over Europe by having a common, continent-wide weather radar system (NOAA's Next Generation Weather Radar (NEXRAD) network) and aviation weather displays (the Corridor Integrated Weather System (CIWS) and future NextGen Weather Processor (NWP)) available in all FAA and airline facilities. This enables common weather situational awareness to be available across the key aviation stakeholders to facilitate effective Collaborative Decision Making (CDM). Such harmonized weather systems do not currently exist across Europe, making CDM more challenging. It is recommended that future work assess the utility of such harmonized systems to enhance European aviation operations.

- *Network management strategies:* in addition to the weather technology differences just discussed, there are differences in network management strategies between the U.S. and Europe. In the U.S., the FAA's ATC System Command Center (ATCSCC) is charged with overseeing and coordinating air traffic management strategies across the continent. Despite the availability of common weather technology across this entire domain, the main automation systems designed to help manage traffic flows (e.g., the Time Based Flow Management (TBFM) system) are limited to the highest density ATC facilities. In addition, these systems are not designed to optimize air traffic management strategies between different regions impacted by weather and/or congestion at the same time. As a result, the ATCSCC does not have automation to support true network-wide optimization. By contrast, the EUROCONTROL Network Manager Operations Center (NMOC) is designed to manage air traffic operations across Europe with a strong network-minded approach. It is recommended that future work analyze how NMOC concepts of operations and flow optimization technologies might be (1) enhanced through the improved weather sensing and forecasting previously discussed, and (2) adapted to improve U.S. ATCSCC operations.

- *System metric standardization:* it was observed during this work that there are similar but not identical ways of categorizing and quantifying causes of delay and associated operational outcomes between the U.S. and Europe. This makes it harder to perform a direct comparison between the behavior of the two regions which may mask important factors. It is recommended that future work develop recommendations to harmonize the classification of weather impacts and operational outcomes between the U.S. and Europe to help with future comparative assessments.

- *ATC harmonization:* weather phenomena do not respect national borders. In order to enhance the ultimate efficiency of the global air transportation system, it will be desirable to extend network optimization concepts to a global scale. As a step in that direction, there could be significant opportunities to further harmonize air traffic management strategies between the U.S. and Europe through all the areas detailed in the preceding bullets. In addition, NAV CANADA is investing in similar network management automation systems to Europe to manage operations in the Canadian domestic and Atlantic oceanic airspace which they control. As such, there could be significant potential benefit to harmonization between FAA, NAV CANADA and EUROCONTROL operations. It is recommended that future work identify the key challenges and opportunities associated with this.

VII. Summary & Proposed Next Steps

This paper has presented a framework for systematically comparing and contrasting weather impacts on key airports in the U.S. and Europe. It has been applied to a selected number of airports to illustrate initial insights that can be obtained through its application. Future research should apply the developed framework to a broader set of airports across different regions to capture a more global perspective on weather-driven ATM challenges. This would allow for a more robust validation of the framework across varying climates and operational environments. Another critical next step is the standardization of metrics between regions to enable more accurate comparisons of weather-related disruptions. This would involve the development of unified metrics that differentiate between direct weather impacts and secondary operational delays. Given the potential for more frequent and severe weather events due to climate change, further work should also focus on integrating future climate models into the framework. This would enable stakeholders to anticipate changes in weather-related disruptions and plan for more resilient ATM systems. Finally, cross-regional collaboration on ATM R&D should be prioritized, with the goal of sharing best practices and jointly developing tools that can mitigate weather impacts on air traffic. A particular focus should be on improving forecasting accuracy and integrating weather data into ATM decision-making in a more seamless manner.

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