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Implications of Lightning Data Uncertainty on Personnel Safety and Operational Efficiency Decisions

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Abstract — **Analyses are presented that quantify the impacts of lightning-induced ramp closures on departing and arriving air traffic. Ramp closures are a necessity to ensure the safety of outdoor personnel servicing gate-side aircraft. Halting outdoor work delays air traffic and causes ripple effects beyond the impacted airport. Today's ramp closure decision-making process is burdened with uncertainty related to the procedures and their implementation, and the lightning data used to trigger ramp closures. This uncertainty needs to be accounted for, as it has implications for ensuring personnel safety and minimizing avoidable operational inefficiencies. The results demonstrate that ramp closures can have substantial impacts on air traffic. Moreover, the choice of safety procedure and varied sources of lightning information yield large uncertainty that renders operators unsure whether their approach is safe and effective. Improvements are needed to better diagnose lightning threats and predict these threats into the near future to enable proactive decisions.**

Keywords — Lightning safety; ramp closure; operational efficiency; commercial air traffic impacts; departure and arrival delays; airport imbalance; uncertainties

I. Introduction

Thunderstorms and lightning pose a serious safety risk to personnel working or pursuing recreational activities outdoors, and they also present a potential hazard to infrastructure and equipment used outdoors. Every year numerous people are injured or killed by lightning [López et al., 1995; Curran et al., 2000; Tan and Goh, 2003; Holle et al., 2005], although it remains difficult to collect accurate data [Lifschultz and Donoghue, 1993; López et al., 1993; Shearman and Ojala, 1999; Adekoya and Nolte, 2005; Ashley and Gilson, 2009]. Airports, sports venues and military operations, therefore, employ safety procedures that include observations and timely warnings of the onset and duration of lightning hazards. These procedures reflect an operator's risk tolerance and willingness to reduce operational efficiency, and they typically vary widely depending on a particular application. What these procedures have in common, however, is that they make use of lightning information (or proxies thereof) to trigger work stops and halt outdoor activities. The ability to accurately monitor and predict lightning threats and associated impacts is crucial to ensure outdoor personnel safety and minimize avoidable downtimes. The report by the Airport Cooperative Research Program [ACRP, 2008] provides a general overview of the problem at airports, safety procedures commonly used, and lightning detection sources available as a basis for making decisions to halt outdoor work.

Expanding upon the ACRP report [2008], Steiner et al. [2013] discuss a range of uncertainties involved in the airport ramp closure decision-making process, including uncertainties related to the lightning data, safety procedures and implementation thereof. The present study examines the impact of lightning-related ramp closures on air traffic (i.e., departures and arrivals) and the implications of uncertainty in the lightning information on personnel safety and operational efficiency decisions made by airline and airport managers. For example, missed lightning strikes, strikes wrongly identified as cloud-to-ground strikes, and strikes located inaccurately may either yield safety risks or inefficiencies (i.e., unnecessary downtime and potential ripple effects from that). From an operator's perspective, understanding these uncertainties and their implications are critical for balancing personnel safety and operational efficiency by means of appropriate procedures, and to build trust in the lightning information used to base decisions on.

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II. Data Analysis and Procedures

Our analyses are based on both air traffic and weather data. The presented results build on combining both sources of information into a single database that was subsequently harvested to quantify traffic impacts of lightning-related ramp closures.

The air traffic data (i.e., airline on-time statistics) were obtained from the Research and Innovation Technology Administration (RITA) Bureau of Transportation Statistics (BTS). This dataset contains detailed information about departure and arrival statistics (e.g., scheduled and actual gate departure/arrival times, departure/arrival delay, wheels-off/touchdown time, and taxi-out/taxi-in time) by airport and airline, including airborne time, cancellation and diversion, and other related information.

For research purposes, NCAR has access to lightning data from three major national and some regional networks. The three most commonly utilized commercial lightning detection networks in the United States are the Earth Networks Total Lightning Network (ENTLN), the United States Precision Network (USPLN) owned by WSI, and Vaisala's National Lighting Detection Network (NLDN [Cummins et al., 1998]).[1] Because they detect lightning mostly at lower frequency (LF), all three networks detect a high percentage of cloud-to-ground (CG) lightning and a lower percentage of in-cloud (IC) lightning [e.g., Betz et al., 2007]. ENTLN also detects in the high frequency (HF) range that in regions with high sensor density (note that HF attenuates faster than LF) may yield increased detection of IC events. Very high frequency (VHF) networks, such as the Lightning Mapping Array (LMA [Thomas et al., 2004]) developed by the New Mexico Institute of Mining and Technology (NMIMT), are regional networks that measure both IC and CG lightning with a very high detection efficiency [Lang et al., 2004]. Systems such as the LMA thus provide the most complete depiction of lightning. Cummins and Murphy [2009] provide an excellent review of lightning detection techniques. Airport and airline stakeholders most commonly use lightning data from LF networks in their ramp closure decision-making processes.

Airline and airport stakeholders employ safety rules that are reactive to a first lightning strike within a critical distance to halt outdoor work and start a waiting period. Each subsequent lightning strike within that critical distance will reset the clock for the waiting period. Outdoor work may resume after there have been no further lightning strikes within that critical distance and designated timespan. The subsequent analyses are based on such safety rules utilizing various sources of lightning information to gauge impact on air traffic in and out of airports. Three safety rules were used in this study, as listed in Table I. They represent a range of typically observed procedures, varying from a very aggressive Rule 1 that some airline stakeholders with advanced decision support tools (e.g., including lightning monitoring and radar data displays) employ to a more conservative Rule 3 used when little support is available and stakeholders are primarily relying on direct sky observations. Many airlines have been relying on something close to Rule 1 or 2.

[1] The order of listing these networks is unrelated to their market share or quality of lightning detection.

TABLE I. Three commonly used lightning safety rules.

Rule	***Critical Distance (miles)***	***Waiting Period (minutes)***
1	3	6
2	5	15
3	6	30

The above safety rules were used to translate time-series of lightning data into time-series of nominal ramp closures, assuming a perfect implementation of safety procedures by the operators. In reality this is not quite the case, as Steiner et al. [2013] highlighted, but it provides for a meaningful basis to quantify the magnitude of the traffic impacts caused by lightning-induced ramp closures. We explored all combinations of lightning data sources and safety rules in our analyses. In order to preserve anonymity of the sources of lightning data and airline stakeholders, we label them as Rules 1 – 3 and lightning Sources A – D, respectively. Moreover, we present the results as bulk statistics and do not reveal a particular location or date when discussing specific examples. The analyses are based on data collected for the Atlanta, GA (ATL), Denver, CO (DEN), Newark, NJ (EWR), Washington Dulles, VA (IAD), Houston, TX (IAH), Orlando, FL (MCO), Miami, FL (MIA), and Chicago, IL (ORD) airports.

III. Impacts of Ramp Closures on Air Traffic

A. *Example of a High-Impact Day*

Figure 1 shows a time sequence of nominal and actually observed ramp closures for two airline operators, plus additional impacting factors related to the weather and FAA traffic management initiatives. Nominal ramp closures are shown for four different lightning data sources and two safety procedures. The nominal ramp closures based on the stakeholder's operationally available lightning information and specific safety procedures are shown in green (Source D). The directly observed actual ramp closures of stakeholders 1 and 2 are shown in gray and purple, respectively. The stakeholder 1 procedures (i.e., using Rule 1 in Table I) yield shorter but more frequent ramp closures than the safety approach employed by stakeholder 2 (using Rule 2).

On this particular day, multiple storms impacted the airport during the afternoon and evening hours yielding several ramp closures in a four to five hour time window. This day has been of great interest to Steiner et al. [2013], because it clearly showed the cumulative effects of multiple ramp closures. The FAA's Air Traffic Control System Command Center (ATCSCC) put out an advisory that day for potential impacts of thunderstorms. There was a short Air Route Traffic Control Center (ARTCC) internal ground stop as well just before a hailstorm impacted the airport. The hailstorm had a marked impact, because the aircraft had to be inspected afterward for possible damage.

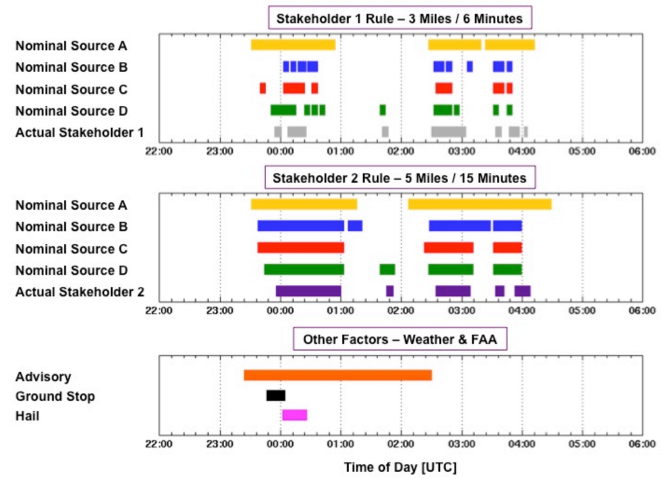

Fig. 1. Nominal and actual ramp closures for two airline operators. Nominal ramp closures are shown for two safety rules (i.e., critical distance and waiting period) and four different lightning networks (Sources A, B, C, and D). The actual ramp closures were directly observed. Other notable factors are shown in the bottom panel.

Comparison of actual to nominal ramp closures reveals potential safety concerns. For example, it took stakeholder 2 several minutes to initiate closures and clear the ramp after the first lightning strike within the critical distance. The response time for stakeholder 1 was notably less, but they also exercise a stepwise reduction in operations approach and thus might have already been more alert. Comparison of the operationally available lightning information (Source D) to the other lightning information sources (especially Source A) shows that the stakeholders' lightning information used for ramp closure decisions was missing an appreciable amount of (mostly IC but also some CG) lightning, which constitutes a safety risk. This comparison also reveals that the ramp closure triggered shortly after 01:30 UTC (Universal Time Coordinated) was really a false alarm (due to lightning location error, confirmed by inspection of data) of the lightning information used by these operators, and none of the other lightning data sources recorded lightning at that time.

Prolonged ramp closures invariably lead to airport operational inefficiencies [e.g., Weber et al., 2007; Brinton and Lent, 2012]. Figure 2 depicts air traffic delays incurred during the case discussed above (Figure 1). Shown are touchdown (in black) and taxi delays (blue) of incoming flights (left panel), as well as gate (red) and taxi delays (orange) of departing flights (right panel). Ramp closures are expected to yield gate delays, as a gate-side parked aircraft cannot get serviced. This is clearly visible in the right panel of Figure 2, where the delays were dramatically increasing during and following ramp closures. There were also some taxi delays incurred by the departing flights, likely caused by the backlog of traffic that built up as aircraft queued up for takeoff.

Traffic delays, however, were also experienced by the incoming traffic. Some delays may have been incurred due to storms en route or locally impacting the arrival fixes, which caused flights into airborne holding patterns, redirection to other arrival fixes, or possible diversions. The impacts of prolonged or multiple ramp closures may also be felt by the arriving traffic after they land while taxiing to a gate. The problem arises when aircraft already occupying gates cannot be readied for departure and are delayed. Eventually no more gates will be available for the incoming flights. Thus, the inbound taxiing aircraft have to wait in a designated area until their assigned (or alternate) gate becomes available. This is clearly seen in the left panel of Figure 2 (and was visibly observed as well). Interestingly enough there were no diversions of incoming flights that day, but there were 7 cancellations for outgoing flights.

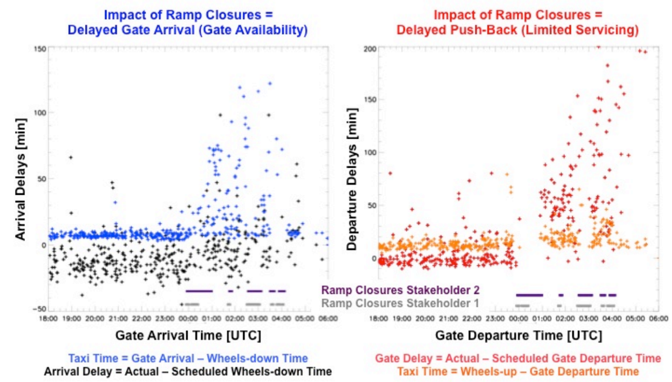

Fig. 2. Observed impacts of ramp closures on air traffic arrivals (left) and departures (right). The observations are from the same case as shown in Figure 1. (Adapted from Steiner et al. [2013]).

One of the key airport operational challenges is to keep the capacity of arriving and departing aircraft in balance to avoid gridlock. Reasons an airport gets out of balance may include emergencies (e.g., loss of a runway due to an unforeseen event) or substantial unexpected weather impacts (e.g., convective storms). Anticipated impacts are typically dealt with at a National Airspace System (NAS) level through traffic management initiatives, such as Ground Delay Program (GDP), Ground Stop (GS), or Airspace Flow Program (AFP) restrictions that aim to reduce the incoming traffic to an airport or region [e.g., Sridhar et al., 2008], but efforts are also underway to include surface management and departure scheduling into the overall planning [e.g., Weber et al., 2007; Brinton and Lent, 2012; DeLaura et al., 2012] to streamline the throughput of terminal air traffic as growing demand is leading to increased congestion and significant delays in particular at the busiest airports in the NAS.

On average, the air traffic into an airport is balanced by the outgoing traffic. Under certain circumstances, such as convective storm impacts, the need may arise to land aircraft at the expense of departing flights to avoid airborne holding or diversions [e.g., Weber et al., 2007]. However, such situations are not sustainable as a backlog of aircraft waiting for departure builds up. In high-impact situations this typically results in a GS and subsequent GDP to facilitate recovery and get the airport back into balance.

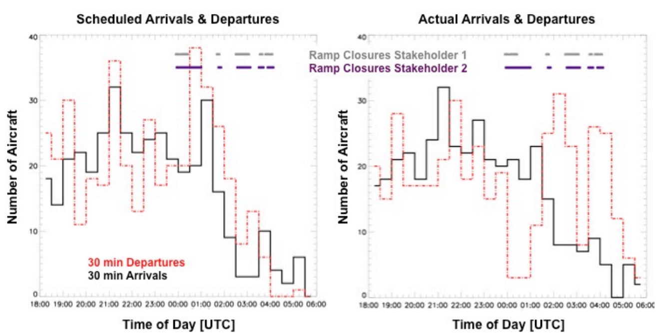

Fig. 3. Impacts of ramp closures on airport balance. Shown are the scheduled (left) and actual (right) arrivals and departures. The observations are from the same case as shown in Figures 1 and 2. (Adapted from Steiner et al. [2013]).

The example discussed previously (Figures 1 and 2) illustrates how convective storms and in particular lightning induced ramp closures can impact airport operations. Figure 3 shows the scheduled (left) and actual (right) arrivals and departures for the airport during that day's thunderstorm impacts and associated ramp closures. The scheduled air traffic was supposed to ramp down after the last high demand period for the day around 1 UTC. Comparison of the scheduled and actual air traffic reveals that the incoming traffic (solid black lines in both panels) was not greatly affected, while departures (red dashed lines) were substantially delayed due to the multiple ramp closures, which brought the airport out of balance. An initial major departure delay was caused by the hailstorm impacting the airport at about 00 UTC (Figure 1), which was accompanied by longer lightning-induced ramp closures for airlines, and necessitated inspection of the aircraft for potential damage after the storm passed. Lightning-related ramp closures associated with this storm and subsequent storms pushed the departures to later times. The airport was able to recover later that evening, because there was not another peak demand period scheduled for that day. However, the locally incurred delays can propagate throughout the NAS causing further delays elsewhere [e.g., Boswell and Evans, 1997; Beygi et al., 2008; Fleurquin et al., 2013].

B. Annual Impact Statistics

Learning from the case study analyses, we compiled annual statistics for flights with a scheduled departure time falling within nominal ramp closures to quantify the impact of ramp closures on air traffic. We counted the number of affected flights and their cumulative gate pushback delays. We also looked at the taxi-out time, as we expected impacts due to airport imbalances caused by the ramp closures. The impacts were characterized as mean delays per affected flight. Since delays can be caused by many other factors besides thunderstorms and lightning, we determined average background delays for gate pushback and taxi-out as well. The difference in delays between the flights affected by ramp closures and the unaffected (i.e., background) flights estimates the true impact of the lightning-induced ramp closures on the air traffic.

Similarly, we analyzed the delays experienced by the arriving traffic, but here we used the actual touchdown time as the metric to decide whether a flight was affected by ramp closures or not. We expected to see delays on both the gate arrivals and taxi-in times. However, the gate arrival delays may have an en-route delay component (e.g., rerouting, airborne holding) to it that is not easily quantifiable [e.g., Campbell et al., 2012]. Thus, we primarily focused on the taxi-in time, as that reveals impacts from a lack of available gates (i.e., still occupied by other aircraft that could not be readied for departure). For the arriving traffic background delays were estimated and differences computed as well.

Figures 4 and 5 visualize the results of our impact analyses for departing and arriving air traffic at one major airport. The figures contain results for the twelve combinations of three safety rules (Table I) and four sources of lightning data. The top two panels show the annual impacts based on number of affected flights and cumulative delays. Depending on which safety rule and lightning information is utilized, many thousands of flights have been counted that fell within a nominal ramp closure, and the associated cumulative delays are substantial. Comparison of the mean gate pushback delays with and without ramp closures (middle panels in Figure 4) demonstrates marked departure impacts (approximately 45 to 50 minutes per affected flight) due to the lightning-induced ramp closures over normal background delays. The impact extends also to the taxi-out time, adding seven to ten minutes over normal taxi time (bottom panels in Figure 4). For the arriving air traffic, on average, flights landing during ramp closures will experience a delay of ten minutes over the normal taxi-in time (bottom panels of Figure 5).

Fig. 4. Departure statistics from 1 January through 31 October 2013 for one major airport. Shown are the total number of flights affected by nominal ramp closures (upper left) and associated cumulative delays (upper right), mean gate pushback delays for flights affected by ramp closures (middle left) and those not affected by ramp closures (middle right), and mean taxi-out time for flights affected by ramp closures (bottom left) and those not affected by ramp closures (bottom right). Nominal ramp closures were computed based on four sources of lightning data (color coded) and three safety rules (grouped together).

Fig. 5. Arrival statistics from 1 January through 31 October 2013 for one major airport. Shown are the total number of flights arriving during nominal ramp closures (upper left) and associated cumulative delays (upper right), mean gate arrival delays for flights arriving during ramp closures (middle left) and those not affected by ramp closures (middle right), and mean taxi-in time for flights arriving during ramp closures (bottom left) and those not affected by ramp closures (bottom right). Nominal ramp closures were computed based on four sources of lightning data (color coded) and three safety rules (grouped together) similar to Figure 4.

Similar analyses were carried out for multiple major airports across the United States. Table II highlights that lightning-induced ramp closure impacts are widespread, although the magnitude of the traffic impacts may vary depending on the complexity of an airport and how close to maximum capacity it operates, and the airport's ability to recover from thunderstorm and lightning impacts considering other nearby airports (e.g., in metroplex regions). The type of weather experienced and the timing thereof matters as well. For example, ORD, ATL, and IAD experience substantial gate pushback delays during lightning-induced ramp closures, notably larger than MCO and MIA which face more pronounced lightning impacts (e.g., number and duration of ramp closures shown in Table III). This emphasizes the need to combine both traffic and weather data when studying aviation impacts (similar to findings by Sasse and Hauf [2003]) instead of simply using weather as a proxy for impact as done in the ACRP [2008] report. The additional taxi-out impacts are largest for ATL and EWR, and again MCO shows the smallest impacts. By far the largest taxi-in impacts are seen for ORD, which is a complex airport running at capacity.

TABLE II. Average gate departure and arrival delays (in minutes), and taxi times (minutes) for eight major United States airports and periods with and without lightning-related ramp closures from 1 January through 31 October 2013. The range of values (minimum to maximum) shown for the gate delays and taxi times is based on using multiple sources of lightning data and various safety procedures as shown in Figures 4 and 5. The average impact (in minutes) per affected flight is derived as the difference between the table's mean values for with and without ramp closures.

Airport	***Metric***	***Ramp Closure min – max***	***No Closure min – max***	***Average Impact***
ATL	Gate Delay	59.11 – 83.48	9.27 – 10.07	61.6
	Taxi Out	29.37 – 35.20	17.91 – 18.06	14.3
	Arrival Delay	36.41 – 45.02	5.58 – 6.31	34.8
	Taxi In	13.14 – 21.68	8.98 – 9.02	8.4
DEN	Gate Delay	44.95 – 77.28	12.86 – 13.76	47.8
	Taxi Out	21.47 – 25.75	14.72 – 14.87	8.8
	Arrival Delay	25.31 – 41.63	6.93 – 7.76	26.1
	Taxi In	11.78 – 24.92	8.62 – 8.69	9.7
EWR	Gate Delay	60.11 – 70.17	14.96 – 15.79	49.8
	Taxi Out	24.46 – 44.98	20.22 – 20.36	14.4
	Arrival Delay	36.18 – 65.89	11.81 – 12.63	38.8
	Taxi In	11.26 – 14.74	8.56 – 8.61	4.4
IAD	Gate Delay	61.17 – 98.20	12.47 – 13.20	66.9
	Taxi Out	15.87 – 32.47	16.55 – 16.76	7.5
	Arrival Delay	37.29 – 63.52	6.26 – 6.69	43.9
	Taxi In	11.59 – 24.54	6.71 – 6.75	11.3
IAH	Gate Delay	35.23 – 55.28	10.47 – 11.10	34.5
	Taxi Out	21.45 – 28.82	15.51 – 15.64	9.6
	Arrival Delay	16.23 – 24.42	4.05 – 4.40	16.1
	Taxi In	9.34 – 13.36	7.38 – 7.42	4.0
MCO	Gate Delay	42.65 – 70.06	9.08 – 10.19	46.7
	Taxi Out	16.52 – 18.14	13.36 – 13.47	3.9
	Arrival Delay	17.65 – 29.20	4.46 – 5.16	18.6
	Taxi In	13.52 – 22.70	7.43 – 7.60	10.6
MIA	Gate Delay	25.99 – 45.70	8.39 – 9.14	27.1
	Taxi Out	22.22 – 23.56	16.17 – 16.46	6.6
	Arrival Delay	11.07 – 17.01	2.59 – 3.22	11.1
	Taxi In	9.68 – 15.17	7.82 – 7.91	4.6
ORD	Gate Delay	70.61 – 104.01	15.06 – 16.02	71.8
	Taxi Out	21.50 – 30.57	16.15 – 16.41	9.8
	Arrival Delay	48.79 – 71.77	8.85 – 9.90	50.9
	Taxi In	18.78 – 42.91	9.32 – 9.43	21.5

TABLE III. Number (counts) and cumulative duration (in minutes) of nominal ramp closures for the airports listed in Table II based on three national lightning detection networks (Sources B, C, and D) and different safety rules (Table I) from 1 January through 31 December 2013. The statistics are based on times when data were available for all three networks (i.e., avoiding effects of data gaps). Note that lightning Source A is not available for all airports and thus was omitted from this table.

Airport	*Source*	*Number of Ramp Closures*			*Duration of Closures*		
		Rule 1	*Rule 2*	*Rule 3*	*Rule 1*	*Rule 2*	*Rule 3*
ATL	B	79	67	74	928	2561	4273
	C	104	129	80	1640	3794	5731
	D	87	130	80	1813	3669	5438
DEN	B	59	57	58	806	2279	3579
	C	94	81	68	1435	3309	5016
	D	54	59	56	563	1812	3258
EWR	B	35	24	31	312	985	1601
	C	44	46	43	664	1614	2435
	D	32	29	29	274	944	1573
IAD	B	32	30	42	458	1152	2162
	C	51	61	51	917	2002	3133
	D	48	43	48	403	1395	2676
IAH	B	86	90	84	1460	3348	5366
	C	121	139	110	2154	4849	7442
	D	103	113	89	1223	3235	5482
MCO	B	122	155	113	2110	4928	7841
	C	163	206	137	3284	7029	10286
	D	157	179	140	2325	5593	9338
MIA	B	126	125	118	1460	4249	7307
	C	220	260	185	3348	7982	12242
	D	174	131	157	1369	4770	8855
ORD	B	63	59	59	995	2183	3549
	C	81	101	70	1761	3455	5029
	D	68	82	56	1032	2316	3528

IV. UNCERTAINTIES AND IMPLICATIONS THEREOF

A. Uncertainties

The uncertainties associated with the lightning safety ramp closure decision-making process are manifold, ranging from an incomplete understanding of thunderstorm electrification processes to measurement and data processing caveats, lightning hazard prediction limitations, varied risk tolerance yielding different safety rules and procedures, and shortfalls in effectively implementing them for many practical reasons.

Thunderstorm electrification and lightning remain active areas of research, as exemplified by many field experiments [e.g., Boe et al., 1992; Rutledge et al., 1992; Lang et al., 2004; MacGorman et al., 2008] and an ever-growing body of literature. Theoretical and laboratory evidence suggests that the primary charging of thunderstorms is associated with collisions between ice particles, and environmental factors (such as the growth regime tied to temperature, relative humidity and liquid water content) are playing a key role in the actual charge transfer during collisions [e.g., Saunders, 1993, 2008; Takahashi and Miyawaki, 2002; Williams et al., 2005]. Differential sedimentation of the low- and high-density ice particles will yield a charge separation within the cloud (note that the charge distribution may be quite complex depending on storm type [e.g., Stolzenburg and Marshall, 2008]) that eventually can lead to electric fields strong enough for the production of lightning. Some aspects of thunderstorm electrification and lightning production remain to be fully understood [e.g., Boccippio, 2002; Yair, 2008; Petersen et al., 2008]. Because of the incomplete process understanding, much of today's lightning prediction capabilities (especially for real-time use) builds on observation and model-based diagnostic and conceptual approaches [e.g., Saxen et al., 2008; McCaul et al., 2009; Potts, 2009; Dance et al., 2010; Dahl et al., 2011; Seroka et al., 2012; Lynn et al., 2012]. The more detailed thunderstorm electrification and lightning schemes put forth by Mansell et al. [2002], Barthe et al. [2005], and Pinty et al. [2013], for example, remain computationally elusive for real-time applications.

The measurement of lightning and associated processing of data constitutes another important source of uncertainty. There can be considerable accuracy differences in determining the location, number and type (IC or CG) of lightning detected, depending on which lightning information system is employed [e.g., Mach et al., 1986; Idone et al., 1998a, 1998b; Naccarato and Pinto, 2009]. The uncertainties are a result of different lightning detection technologies, sensor network densities, and data processing associated with the various national and regional lightning measurement systems. Since the lightning measurements and data processing algorithms continue to be improved, the detection accuracy of lightning events will change over time and may also vary geographically [e.g., Wacker and Orville, 1999]. Typically, the regional total (i.e., IC and CG) lightning measurement systems provide lightning information with a higher detection efficiency and accuracy than the national networks currently available to airport and airline stakeholders.

Due to a lack of common guidance, airline and airport operators have varied procedures in place to ensure safety of outdoor personnel. A commonality of all approaches is the closing of a ramp in response to a first lightning strike within a critical distance of the airport (i.e., a reactive approach) and then waiting for a period of time until it is deemed safe again to resume outdoor work [ACRP, 2008]. The primary source of uncertainty is related to the critical distance (from the terminal area where people work outdoors) and timing (i.e., waiting period after the last lightning strike) criteria. A wide range of values is in use, yielding situations where multiple airlines may be utilizing different criteria at any given large airport. Without a doubt, airlines aim toward minimizing the downtime caused by lightning-related ramp closures in order to maximize efficiency. It is also apparent that airlines display varied risk tolerances. Moreover, Steiner et al. [2013] emphasize that aspects of the human cognition and behavior have to be considered. There are multiple factors related to a decision-maker's trust in the safety procedures and tools at their disposal, and how effectively the procedures are implemented (e.g., how efficiently closures are communicated to the outdoor workers and how fast a ramp can be cleared). Sometimes decision makers can be distracted by other operational demands (thus, yielding a delayed alert and ramp closure or none whatsoever) or their decisions may be influenced by what other airlines are doing in a particular situation. Finally, many regional and small airports have no established lightning warning procedures in place at all. Most of these airports do not have access to lightning detection information and rely on visibly seeing lightning in the local area. In addition, they may lack formal means to notify personnel working outside in the airport area.

B. Implications

All of the above-mentioned uncertainties have implications for the lightning safety-related ramp closure decision-making process. As Figures 4 and 5 reveal for a single major airport, and Table II echoes for multiple airports across the United States, choosing one safety rule over another or working with varied lightning data sources can make a marked difference in expected air traffic impacts. Clearly, a lower risk tolerance and use of a more conservative safety rule (e.g., Rule 2 or 3) will yield larger impacts. On the other side, a more aggressive rule (e.g., Rule 1) will result in higher safety risks, but the traffic impacts may not be as substantial. While it is relatively straightforward to characterize the traffic impacts, quantifying the safety risk for personnel working outdoors near thunderstorms remains challenging and needs further attention [e.g., Tarimer et al., 2012]. For example, Ashley and Gilson [2009] showed that the risk of a fatal lightning strike depends on the type of thunderstorm and is highest for unorganized thunderstorms. Once the risks and traffic impacts are both quantified one can use economic metrics to determine a meaningful balance between personnel safety and operational efficiency that might be acceptable to airport and airline operators.

There are notable differences in the lightning information as well that translate into varied traffic impacts, as seen from Figures 4 and 5, and Table II. One particular concern with the lightning data relates to missed, misclassified or mislocated strikes. Missed CG strikes are a significant safety issue, while mislocated strikes may trigger unnecessary ramp closures (e.g., false alarm triggered by the operationally used lightning Source D after 1:30 UTC) that yield operational inefficiencies. Both types of concerns are visible in Figure 1. Using the regional lightning Source A as a baseline (because of its most complete lightning detection efficiency), Table IV shows that false alarms have been found with the national lightning networks (Sources B, C, and D) and that there may be non-negligible impacts on air traffic from those false alarms. Thus, uncertainty in the lightning detection, classification, and location has notable implications for the operational utilization of such information.

TABLE IV. Traffic impacts (number of flights and minutes of pushback delays) at one major airport as a result of false alarms based on three safety rules (Table I) and national lightning detection networks (Sources B, C, and D) from 1 January through 31 October 2013. The lightning data Source A is used as baseline, because of its most complete depiction of lightning activity. A false alarm is identified when Sources B, C, or D yielded lightning-induced ramp closures, but Source A did not observe any lightning. Flights within those false alarm periods were counted.

Source	*Number of affected Flights*			*Cumulative Gate Delays*		
	Rule 1	*Rule 2*	*Rule 3*	*Rule 1*	*Rule 2*	*Rule 3*
B	30	23	12	601	314	348
C	86	228	320	5083	7321	9007
D	48	143	162	3111	5415	4225

Current safety procedures are reactive to a first lightning strike within a critical distance. Unfortunately, this first lightning strike may already be harmful to people working outdoors. Moreover, especially during stressful high-demand situations, an initial lightning strike (sometimes even several) may be ignored to keep operations going. Once a ramp closure is initiated, it typically takes a few minutes before outdoor personnel have cleared the ramp and moved inside to safety, as shown in Figure 1. Current reactive approaches, therefore, may incur notable safety risks. Furthermore, as Table V shows, incomplete lightning detection (i.e., misses) are pretty common. Granted, not all of these misses are CG strikes, but likely IC lightning events. Nonetheless, any type of lightning near outdoor personnel is a safety concern and should be identified as such.

TABLE V. Periods of false alarms (i.e., inefficiency concern), hits, misses (safety concern), and correct nulls – all expressed in minutes – at one major airport (same as in Table IV) based on three safety rules (Table I) and national lightning detection networks (Sources B, C, and D) from 1 January through 31 December 2013. The lightning data Source A is used as baseline, because of its most complete depiction of lightning activity.

Rule	*Source*	*False Alarms*	*Hits*	*Misses*	*Correct Nulls*
1	B	32	774	1529	346129
	C	170	1265	1038	345991
	D	80	483	1820	346081
2	B	43	2236	2231	343959
	C	405	2904	1563	343597
	D	206	1606	2861	343796
3	B	48	3531	2998	341900
	C	597	4419	2110	341351
	D	269	2989	3540	341679

The overarching implication of all these uncertainties is that a better characterization of the lightning hazard is needed (likely based on incorporating multiple sources of relevant information, which will improve recognizing lightning threats from anvil clouds and help reduce false alarms as well) and that decision support tools have to include appropriately designed buffers to account for uncertainty (especially if used in a reactive way) and to allow for varied user-based risk tolerances. Looking forward, a capability to predict lightning hazards into the near future would enable a heads-up of imminent impacts that can be used for more proactive measures, benefiting personnel safety and operational efficiency alike.

V. Conclusions

Lightning-induced ramp closures are a necessity to ensure the safety of outdoor personnel servicing gate-side parked aircraft. Our analyses determined that ramp closures cause notable air traffic impacts on both departures and arrivals. The inability to ready aircraft for departure during ramp closures will result in a delayed gate pushback time (on average amounting to several tens of minutes per affected fight). Prolonged or multiple successive ramp closures can create a backlog of departing aircraft that will have to queue up for taxiing out after operations resumes again, which yields additional delays (on average five to fifteen minutes). Notable delays were also found for arriving flights in form of increased taxi-in times (on average five to twenty minutes), which is a consequence of unavailable gates that remain occupied by aircraft unable to get readied for departure.

Our research has shown that the ramp closure decision-making process is burdened with a number of significant uncertainties related to the thunderstorm electrification, the measurement and processing of lightning data, and the safety procedures and effectiveness of implementing them. The scientific understanding of the processes leading to thunderstorm electrification and lightning discharges is incomplete, which renders the diagnosis and very short-term prediction of lightning threats somewhat uncertain (note that outlook times beyond an hour are associated with much larger uncertainty). This might be part of the reason why today's approaches to lightning safety remain reactive (rather than proactive) relying heavily on lightning observations. Yet the lightning data were found to exhibit their own share of marked uncertainty related to the measurement technique (i.e., sensors), network detection efficiency (number and arrangement of sensors), and subsequent data processing (algorithms to classify IC versus CG strikes and locating them). Missed lightning activity or misplaced strike locations are not unusual, and these inaccuracies may yield either safety risks or operational inefficiencies (e.g., unnecessary ramp closures). The safety rules typically employed by airport and airline operators reflect their risk tolerance aiming to minimize downtime. Moreover, the implementation of these safety procedures is affected by the human cognition and behavior, often producing delayed or inconsistent ramp closures that can yield avoidable safety risks for outdoor personnel and operational inefficiencies.

All these uncertainties have implications on personnel safety and operational efficiency. We are convinced that a better characterization of the true lightning hazard is needed as basis for improving the safety of outdoor personnel and minimizing avoidable operational inefficiencies. An effective ramp closure decision support will have to combine multiple sources of relevant information (e.g., radar and lightning data from more than one source) for a robust diagnosis of lightning threats. This will also help reduce missed lightning hazards and false alarms. Appropriate buffers will have to be built into the decision support to account for the varied and notable uncertainties, possibly considering the type of thunderstorm encountered. Moreover, a nowcasting component will enable recognizing lightning threats before the impact to allow for proactive actions. And finally, a shared situational awareness among all airport stakeholders and appropriate training will go a long way to minimize avoidable lightning impacts on air traffic operations while maintaining outdoor personnel safety.

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