Impact of Lightning Strikes on National Airspace System (NAS) Outages

A Statistical Approach

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***Abstract*— Although it is reasonably well accepted that lightning strikes are a significant cause of outages on the National Airspace System (NAS), there remains a serious lack of comprehensive analyses providing sound estimations of convective weather impact. The results and methods available generally cover specific outages and try to determine their causes by comprehensively analyzing the lightning strikes that occurred in the vicinity of the system. Such methods are inappropriate when trying to evaluate the global impact of convective weather on very large systems such as NAS, which is composed of more than 70,000 systems. In this paper, a statistical method is developed to estimate the number of outages caused by lightning strikes, which is robust on both the time detection of the outage and the localization of the strikes. In addition, we present results of its application on the NAS outages between 1999 and 2005.**

***Index Terms* - component; lightning strikes; outages; NAS; NLDN; logit model**

I. INTRODUCTION

The safety and efficiency of air transportation within the United States (US) largely relies on the reliability of the National Airspace System (NAS). Lightning strikes are believed to be one of the major causes of electrical power interruption and occur during critical weather conditions [1] for airborne aircraft.

The method presented here is based on the National Lightning Detection Network (NLDN) observations that represent more than 95% of the lightning strikes in the continental US [2] and provide the time of the strike, its location and the intensity. The data base contains the location of the first stroke of each lightning strike which can cause errors of until 10 km, based on the algorithm used by the NLDN [3].

The information concerning the outages, provided by the Federal Aviation Administration (FAA) was gathered manually by the technicians in charge of the maintenance of the NAS, utilizing a system of Cause Codes to classify the different categories of outages.

A preliminary analysis of the problem was carried out in an attempt to establish an initial relation between lightning strikes and outages. All strikes that happened in the continental US between 1999 and 2005 were attributed to each of the 20 Air Route Traffic Control Centers (ARTCC) and to each month. Then, values were plotted against the number of outages occurring in the respective ARTCC to determine if a general pattern exists (Figure 1). Although a small positive correlation is noticeable, results are unusable for further applications as in many cases more lightning strikes do not imply more outages. Indeed, more advanced tools based on the characteristics of lightning strikes are required to explain the outage process.

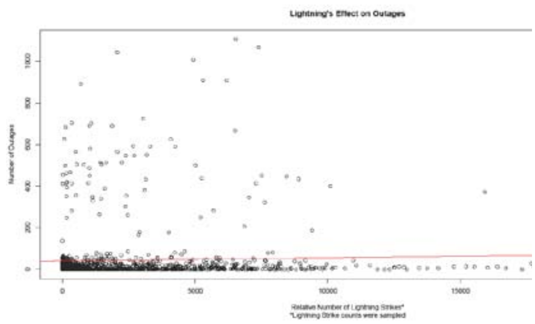

Figure 1. Plot of the number of lightning strikes during a month and inside a given ARTCC against the number of outages inside the same region and over the same period of time

II. CREATION OF THE DATA BASE

A. Data Management

The data used for this study contain all the lightning strikes in the continental US between March 1999 and November 2005 (recorded by the NLDN). The data contain both cloud-to-cloud (CC) and cloud-to-ground (CG) lightning strikes. Beside interferences, the former do not impact the NAS systems significantly and are therefore ignored in the study. For each strike, the data set provides the location, the time and the magnitude (in kilo amperes) but does not give the number or the location of each stroke.

The list of all the outages that concerned the NAS during the same period constitutes the second data set. For each outage, the information available is: the type of system, its location, the beginning and end of the outage, and reported cause of the failure. The Cause Code (i.e. code) corresponding to "Convective Weather" is 85-3 (Weather Effect – Lightning Strikes) and all outages with a different code are not used to develop the model. It is interesting to note that the time of the beginning of the outages is the time when the outage was detected and not necessarily the time when it occurred. Finally, as the NLDN covers only the continental US, all the outages concerning systems located in the ARTCC of Honolulu (ZHN), Anchorage (ZAN) and not on the continent (SCT) were also removed. The number of remaining outages is close to 900.

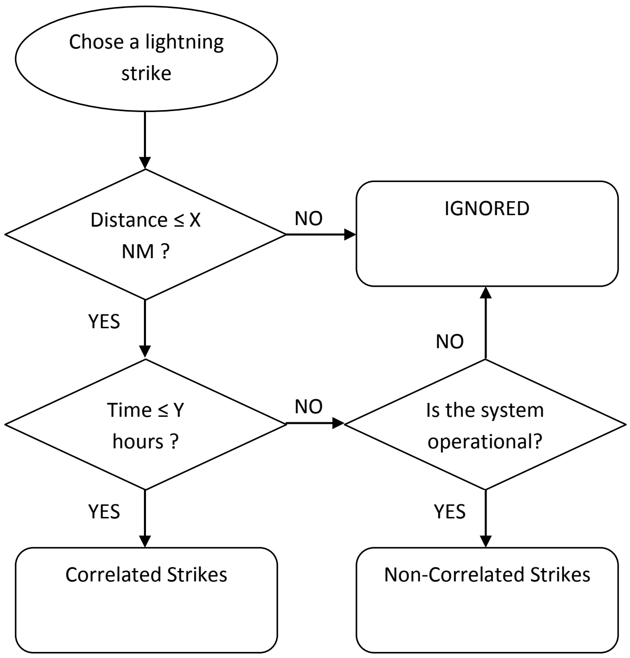

Figure 2. Algorithm applied to each outage and for all lightning strikes

B. Correlated / Non-Correlated Strikes

The input of the model is built with 2 distinct selections of lightning strikes: one group that caused outages (Target Strikes) and another that occurred in the vicinity of the systems but that did not cause any outages (Non-Correlated Strikes). The former cannot be directly created considering the lack of precision of the NLDN data and therefore a larger (and simpler to define) group of strikes that might have caused an outage is required (Correlated strikes):

- Correlated Strikes: strikes that might be responsible for the outage,
- Target Strikes: strikes that are considered as responsible for the outage,
- Non-Correlated Strikes: strikes that did not cause any outage,
- Undetermined strikes: strikes that do not belong to the two previous categories.

The Undetermined strikes are mainly strikes that occurred in the vicinity of the system but when it was not operating for any reason (maintenance, outage, etc). Strikes are first selected based on a spatial criteria of X nautical miles and then attributed to the different groups according to a temporal criteria (Figure 2).

C. Time and Space Window

The separation between the different groups of strikes is based on a time criterion and a space criterion. The name used for the study is "Time and Space Window" and corresponds to an X NM radius circle around the system and a period of Y hours before the outage. The final values for X and Y are respectively 5 NM and 48 hours, which resulted from the analysis of the Cause Code 85-3 outages. An adequate Time and Space Window must give both a high level of correlation as we expect that most of the Cause Code 85-3 outages are caused by lightning strikes and a small number of correlated lightning strikes to facilitate the target strikes extraction. The level of correlation represents the ratio of the number of correlated events (outages) for a period over the total number of events (outages) for the same period. An outage is

Table 1: Level of Correlation as a function of the Time Window size and the Space Window size

		Time									
		5min	**30min**	**1h**	**6h**	**12h**	**24h**	**48h**	**72h**	**96h**	**120h**
Distance (NM)	**0.1**	0%	1%	2%	3%	4%	5%	5%	5%	5%	5%
	0.25	2%	8%	12%	17%	20%	23%	25%	25%	25%	25%
	0.5	6%	16%	22%	32%	37%	42%	46%	46%	47%	47%
	0.75	10%	22%	28%	41%	46%	52%	56%	57%	58%	59%
	1	13%	24%	31%	44%	50%	57%	62%	64%	64%	65%
	2	20%	32%	40%	53%	60%	67%	72%	74%	75%	76%
	3	25%	35%	42%	57%	62%	70%	76%	78%	80%	81%
	4	28%	38%	44%	58%	65%	72%	79%	82%	83%	84%
	5	30%	40%	46%	61%	66%	74%	80%	83%	84%	85%
	10	31%	41%	48%	63%	69%	78%	85%	87%	88%	89%
	15	32%	42%	49%	64%	70%	79%	87%	89%	90%	91%

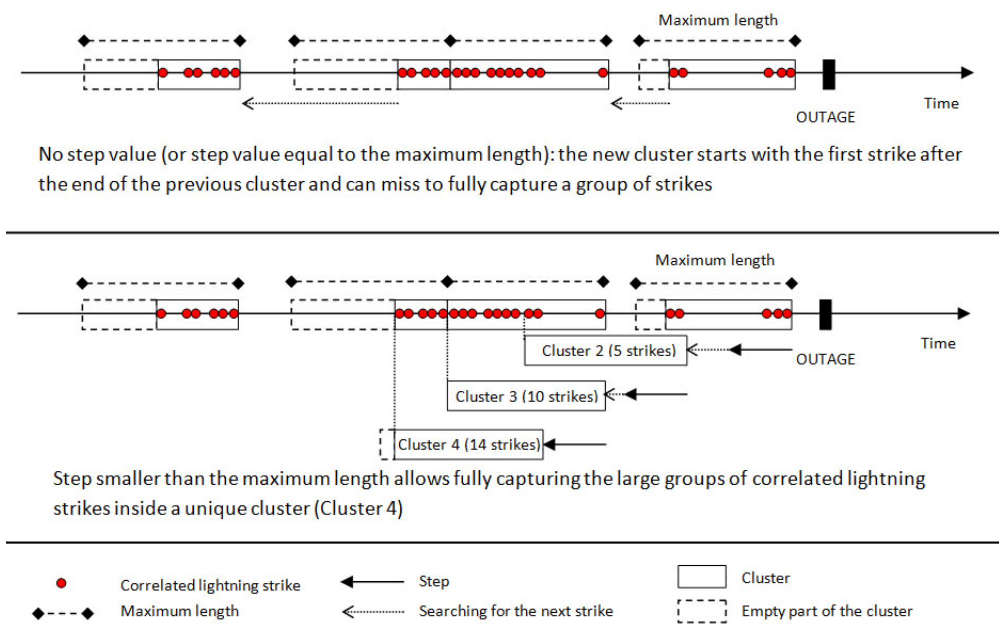

Figure 4: Comparaison between clusters that can overlap and clusters without a step value

considered correlated if its Time and Space Window contains at least one lightning strike.

As the Time and Space window becomes larger, more irrelevant strikes are correlated. The definition of the window must take into account this tradeoff between the Correlation Ratio and the relevance of the correlated strikes. The Time Window represents the maximum period before an outage during which a strike is considered as a potential cause of outage. Although the outage mechanism is not perfectly understood, it is well accepted that the time between a strike on the system and the failure will be generally very short. Associated failures are typically caused by over intensity resulting in excessive heat inside the system and thus occur almost instantaneously after the impact [3]. As the lightning data and outages data have respectively an average time precision of 5 µs and 1 minute, a time window of a few minutes should capture most of the cases [3]. The main issue comes from the detection time of the outages. Systems equipped with automatic outage reports are automatically considered as "down" as soon as the outage occurs. For other pieces of equipments such as radars, which are closely monitored, outages are also very likely to be detected within a few minutes. However, for other systems, such as Precision Approach Path Indicator (PAPI), outages can be only detected in the case where someone tries to use the system or during a routine check. Unfortunately, no studies have been carried on to determine the average detection time of outages depending

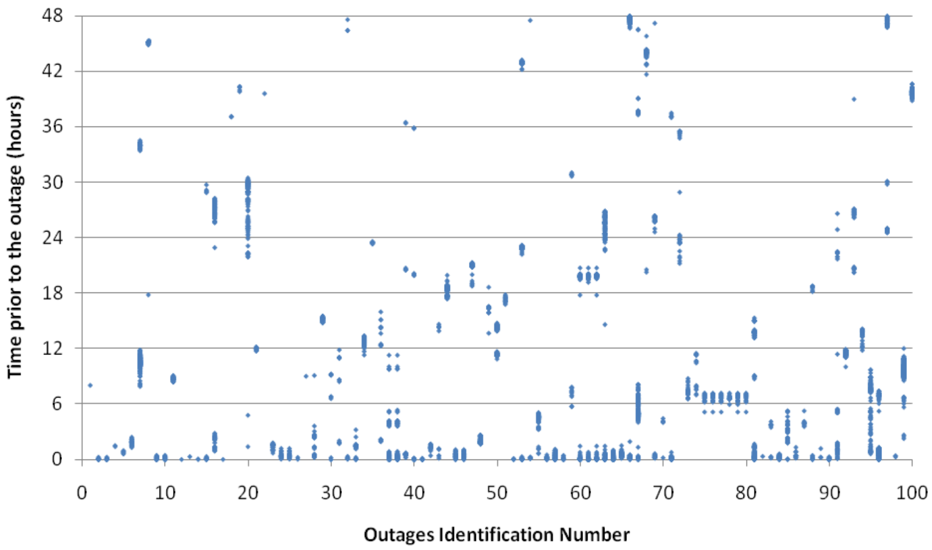

Figure 3. Spatial representation of the correlated lightning strikes. Each dot represents a strike that occurred within 5NM of the system indicated on the horizontal axis. The time between the lightning strike and the outage of the concerned system is on the vertical axis?

on the type of systems and their location. Different simulations performed with Time windows between 1 minute and 5 days proved that the detection of an outage can take up to several days although more than 50% of the correlated outages have at least one lightning strike in the hour prior to the failure (Table 1).

The Space Window represents the size of the vicinity in which strikes are considered as a potential cause of outage. Its size is the radius of the circle and is centered on the system. In this case, the incertitude mainly comes from the NLDN stroke gathering algorithm [3]. Different simulations with space windows between 0.1NM and 15NM showed a similar behavior compared to the time window. All curves tend to a limit value after 10 NM. Once again, although some outages have their closest correlated lightning strike located at more than 10 NM, more than 50% of the correlated outages have at least one lightning strike within 0.5 NM (Table 1).

The final size of the Time and Space Window directly determines the correlated strikes, among which the target strikes, input of the statistical model, will be selected. Its definition is based on a tradeoff between the number of observation that should be as large as possible and the relevance of the input. Each time the Time and Space Window increases, new observations are added but the probability that they are actually involved in the outage process decreases. As showed in Table 1, the correlation ratio reaches a limit in both cases. Those values are considered as the maximum number of observations which can be used and it is decided to use only 95% of them inside the model. The last 5% of correlation implies a multiplicative factor of 2 to 3 for the time and space parameters and adds a large number of correlated strikes which relevance is very low.

D. *Strike Definition vs Cluster Definition*

Strikes are defined as the strikes that caused the outage as opposed to the correlated strikes, which are the strikes that might have caused the outage. However, this definition results in many possible solutions as no general rule or model exists to determine, among a group of strikes, which one actually caused the outage.

Clusters were created to solve the problem of best strikes selection. The idea is to gather correlated strikes over a period of time and then consider the whole cluster as the outage cause. This principle was born from the observation of the time localization pattern of Correlated Strikes that tend to appear in groups of high time density (Figure 3). Each dot represents a correlated lightning strike and is positioned on the graph depending on its related outage (horizontal axis) and time between the strike and the outage reported time (vertical axis). Because all the represented strikes belong to the Correlated Strikes group, they are all located within a range of 5NM from the system. As lightning strikes happen during thunderstorms, multiple strikes generally hit the vicinity of the system within a short period. The goal of clusters models is to isolate those laps of time of high convective activity and consider them as the cause of the outage.

Clusters are fully defined by 2 different characteristics:

- Maximum Length: their maximum duration in time. Clusters with maximum lengths between 5 minutes and 48 hours were simulated to find the most significant values. The length of the cluster is defined by the last strike inside the time interval, thus most clusters are shorter than their maximum value. The "maximum length" is set to 48 hours to keep an even comparison between Correlated and Non-Correlated Clusters as correlated strikes are defined for a period of 48 hours. A larger length would add strikes inside the Non-Correlated Clusters defined over the 7 years of the study but not to the Correlated-Clusters.
- Step: the minimum time between the beginnings of two consecutive clusters from a same outage. For simulations, clusters work as time windows which are slid from the step value until another strike is found. For each outage, the first cluster starts with the last correlated strike (the closest in time from the outage reported time), and is then moved from the step value "in the past" and keeps sliding in the past until it finds a new strike. The process is repeated until all the strikes have been attributed to at least one cluster. The step value's purpose is to prevent the "cluster window" from missing a group of strikes by cutting it in two different parts (clusters). It is possible to ignore the step parameter by choosing its value equal to the maximum length. In this case, clusters are never overlapping each other. Because all strikes have to belong to at least one cluster, steps values are always smaller or equal than the maximum length of the cluster, even if this causes some strikes to belong to more than one cluster. The step value should not be too small to limit the number of appearance of the same strikes inside different clusters which can cause correlations issues with the statistical model. Thus, the typical steps values are the maximum length multiplied by 1/3, 1/2 and 1. It appears that steps values have very little impact on statistical model parameters and levels of goodness although steps of half the maximum length tend to give better results in this case. In addition, "1/2-steps" clusters limit the multiple occurrences of strikes to two.

Therefore, for the rest of the study, all clusters used a step value equal to the half of their maximum length.

III. STATISTICAL MODEL

A. *Shape of the model*

The statistical model used to process the input is the binary logit model:

$$\text{logit}(p_i) = \log(p_i/(1 - p_i)) = k + \beta_1 X_{1\,n} + \ldots + \beta_n X_{i\,n}$$

This model is used because of the nature of the input that uses a time criteria to separate the Correlated and the Non-Correlated strikes. When the model is applied, it is limited to the clusters located inside the Time and Space Window. As a result, the sum of the output corresponds to a "partial sum" and does not represent the real estimation of the number of Confirmed Outages. For this reason, an extra tool is required for the analysis and the tool that seems to work the best is the threshold method proposed here, followed later by an aggregation of the models.

The Decision Threshold (DT) of a model is a fixed value above which an observation is considered as a "1". In other terms, the model gives for each cluster a probability that this cluster actually caused an outage. If this value is above the DT of the model, the cluster is considered as a "1" (caused an outage). The DT of each model is set to maximize the distinction between correlated and non correlated strikes i.e., the proportion of right answers given by the model on the input data. The model is "correct" if the predicted status of the cluster is the same as the real one. The 4 different scenarios, represented by letters from A to D (Table 2), are:

- 0-0 (A): Non-correlated strike considered as not a cause of outage by the model – Correct answer
- 0-1 (B): Non-correlated strike considered as a cause of outage by the model – Wrong answer
- 1-0 (C): Correlated strike considered as a not a cause of outage by the model – Wrong answer
- 1-1 (D): Correlated strike considered as a cause of outage by the model – Good answer

Table 2: Definition of the goodness of the model

		Prediction of the model	
		0	1
Real Value	0	A %	B %
	1	C %	D %

For each model, the DT is adjusted in order to maximize the value of the goodness.

B. Selection of Parameters

In this study, the selection process for parameters is not based on the complex analysis of failure mechanisms. There is extensive literature presenting advanced electromagnetic models in which the goals are to precisely predict the propagation process based on observations made by sensors located near or on the systems. Such a level of precision is not realistic because of the lack of precision of the data available but fortunately, it is also not needed given the statistical point of view of the study. Our approach is more intuitive because it consists of parameters that seem more relevant to the model and have better statistical significance. The first step of the process is the creation and selection of potentially meaningful metrics. Parameters such as the intensity of the strike or the distance between the strike and the system undoubtedly have an impact on the outage mechanism. In addition, the type of system of the area on which it is installed may also play a role. We also developed Hybrid metrics to increase the versatility and precision. Given that the maximum expected precision of the NLDN is 500 meters, all values of distances smaller than that were modified to be equal to 500 meters. The second step is the elimination of non-statistically relevant parameters. First, they have to match the intuitive positive or negative effect they have on the model. For example, intensity should have a positive impact (positive sign for β intensity) meaning that the higher the intensity, the higher the chance for an outage. Then, the significance, represented by the *p*-value, designates the statistically sound metrics. However, because of important correlation issues between the parameters, the *p*-value can strongly fluctuate from one model to another for a given parameter.

Table 3: Rejected Parameters

- Type of equipment
- Duration of the Cluster
- Number of Strikes
- ARTCC
- Month / Season
- Time Density
- Highest Intensity/Distance²
- Highest Intensity²/Distance²
- Sum of Intensity/Distance²
- Sum of Intensity²/Distance²
- Duration of the outage

ARTCC parameters are however a special case. Although it appears natural to take into consideration the region where the outage occurred, the definition of the Correlated Strikes already covers this part. Regions with a larger convective activity will see more lightning strikes in their Time & Space Windows. In addition, the characteristics of the strikes relative to a special region (violent short storms for example) are also covered by the characteristics of the strikes. As a result, taking into account the ARTCC would result in a redundancy, which is why they are not used in the models. The equipment types also required a special treatment as they generally result in high p-values, mainly because of the small number of observations for certain types of systems. Large *p*-values are not acceptable in terms of consistency but the gathering of some equipment types into a larger group solved this problem. To determine this new larger group called "ZZZ", the outputs of simulations obtained with different cluster lengths were compared and all non-significant equipment types were moved into this group. The "ZZZ" group is considered neutral and serves as a basis for the value of the parameters of the other groups and therefore do not appear in the models' output (the estimate value is 0).

Table 4: Description of the final parameters

Parameter Name	**Full Name**	**Description**
H Int over dist	Highest Intensity over Distance	Highest value of Intensity/Distance observed among the strikes of the cluster
H Int	Highest Intensity	Highest value of Intensity observed among the strikes of the cluster
H Dist	Smallest Distance	Smallest value of Distance observed among the strikes of the cluster
S Int over dist	Sum of Intensity over Distance	Sum of all the values of Intensity/Distance of the strikes contained inside the cluster
New Type1	Modified type of equipment	Type of equipment that underwent the outage. Some equipment types are gathered inside the "ZZZ" group

Table 5: Caracteristics of the models depending on the cluster length

	Goodness	DT	Confirmed
48 hours	40%	0.026	1730
24 hours	43%	0.026	1567
12 hours	46%	0.022	1884
6 hours	47%	0.020	1796
2 hours	49%	0.014	2534
1 hour	50%	0.010	2238
30 min	53%	0.008	2796
15 min	53%	0.004	2688
5 min	53%	0.002	2434

Table 6: Statistical Model (1hour-long clusters)

Parameter	**Estimate**	**Standard Error**	**Wald Chi Square**	**Pr>ChiSq**
Intercept	-4.3930	0.1068	1693.178	<.0001
H Int over dist	0.00761	0.000718	112.1786	<.0001
H Int	0.00369	0.00123	9.0080	0.0027
H Dist	-0.3545	0.0419	71.7399	<.0001
S Int over dist	0.000166	0.000037	20.6793	<.0001

The 9 different models are then applied to outages codes different than Cause Code 85-3. First, the Time & Space Windows are created for each outage and then clusters of the different lengths are defined and the corresponding models (with their corresponding codes) are then applied. If, for a given outage and a given cluster length, the models return a value higher than the DT, the outage is considered as a "Confirmed Outage". The total number of Confirmed Outages is fairly constant among the different models, but the results for a given outage might vary. To consolidate the results, a matrix containing all the outages and the corresponding output for each model is created (Table 9). Then, depending on the desired level of conservativeness, it is possible to select a new threshold above which an outage will be ultimately considered as caused by convective weather. The threshold is generally chosen as at least the majority of the models, which corresponds to 5 in our case. Thus, in this example, only outage 2 is considered as caused by convective weather.

IV. CASE STUDY

The model has been developed using 987 outages reported as caused by lightning strikes (Cause Code 85-3) between 1999 and 2005. While building the Time and Space Windows, it appeared that 200 of Cause Code 85-3 outages did not have a single lightning strike located within 5 NM and 48 hours before the failure. As a result, it is very unlikely that convective weather is responsible for those outages.

The Non-Correlated Strikes were obtained by processing 621 randomly selected outages during 24 months (also randomly selected), which led to a total number of 1,800,000 Non-Correlated Strikes. We then created the 9 sets of clusters with the different lengths (48 hours, 24 hours, 12 hours, 6 hours, 2 hours, 1 hour, 30 minutes, 15 minutes and 5 minutes) and computed *a binary logit model* for each of them. Table 6 is an example of the models for clusters of 1 hour. In this version, equipment-types parameters are not included as they proved to have poor statistical significance.

Then, all the outages contained in the FAA data were filtered to consider only outage codes where lightning strikes could be the original cause (Table 7) and Time and Space Windows were created for them. Unsurprisingly, the correlation levels observed are lower than for the Cause Code 85-3 outages, 27 % vs. 80%. Finally, we applied the 9 statistical models to the corresponding sets of clusters and used the aggregate method presented above (Table 10). The total number of outages reported under "other codes" but considered by the model as caused by lightning strikes spans between 1381 and 3013 which implies a significant modification of the original number.

Several reasons can explain the apparent differences between the original data and the output of the model. First, even when the cause of the outage is not clear, people in charge of the maintenance are likely to indicate "lightning strikes" if some convective activity was present in the region. Secondly, the FAA Cause Code system indicates the ultimate cause of the outage but does not indicate its early cause. For example, for outages reported under "Power Supply" (Cause Code 80-3), nothing indicates what actually caused the loss of power. The first effect tends to overestimate the number of outages caused by lightning strikes whereas the second one underestimates it. However, according to the results of the model, the magnitude of the second effect is larger (plus 1381-3013 versus minus 200 for the first effect).

Table 7: List of outage codes considered for the estimate

Code	**Number**	**Category**	**Sub Category**
80-3	611	Equipment	Power Supply
80-7	13886	Equipment	Unable to Determine Cause
80-F	214	Equipment	Facility Power and Support Systems
81-3	41	Non-FAA Lines/Circuits	Power
81-6	8	Non-FAA Lines/Circuits	Environmental Causes
81-7	99	Non-FAA Lines/Circuits	Unknown
82	4045	Prime Power	-
83	1156	Standby Power	-
84-3	104	Interference Conditions	Radio frequency interference
87-0	6992	Unknown	-

Table 8: Summary of the number of outages considered for the different steps

Model Creation	
Number of 85-3 outages (after cleaning)	987
Number of correlated outages	787
Results (Other Codes)	
Total number of outages	65558
Number of outages after cleaning and code selection	27156
Correlated outages	7299

Table 9: Exmaple of aggregate model

List of outages	48 h	24 h	12 h	6 h	2 h	1 h	30 min	15 min	5 min	Total
Outage 1	1	0	0	0	0	1	1	0	0	3
Outage 2	0	1	1	1	1	1	1	1	1	8
…	…	…	…	…	…	…	…	…	…	…
Outage n	0	0	0	0	0	0	0	0	1	1

Table 10: Number of confirmed outages using the aggregate method

Number of models confirming the outage	Cumulative number of confirmed outages
All	1381
8	1551
7	1772
6	1888
5	2202
4	2394
3	2629
2	2837
1	3013

V. CONCLUSION

The correlation between lightning strikes and outages exists and can be captured by statistical methods. To achieve this goal, it is crucial to take into account the important data inaccuracies and to focus more on periods of high convective activity rather than on specific strikes to determine the causes of outages. Both strike localization issues and imprecise outage report times imply a high incertitude in the Target Strikes selection and forced us to introduce the Time and Space Window: a spatiotemporal area of 5 nautical miles and 48 hours associated which each outage and inside which all strikes are considered as a potential cause of outages. Even with those large values, for 22% of the outages reported as caused by lightning strike (Cause Code 85-3) we were not able to find a single lightning strike inside the Time and Space Windows. In these cases, it is very likely that these outages are not related to convective weather and their FAA outage code should probably be modified.

Because of the previous definition of the Time and Space Window, numerous strikes distributed over large periods of time might be responsible for a given outage and no characteristics allow a reliable selection. For this reason, we favored an approach based on clusters gathering lightning strikes over periods of time spanning from 5 minutes to 48 hours to create *independent regular binary logit models*.

Then, we applied those models to a selection of codes dealing with power supply failure and unknown causes. The resulting subset contained about 27,000 outages among which 7,300 had at least one lightning strike inside their Time and Space Window. In a number of cases spanning from 1381 to 3013 outages, lightning strikes are likely to be the initial outage cause although these numbers should be carefully considered.

Finally, two major sources of inaccuracy limit the precision of the models. The first and easiest to fix is the localization precision of the strikes which cause the correlation of too large of a number of lightning strikes. More comprehensive data providing the exact location of each stroke is available and would reduce the Space window to an average of 500 meters. The second issue is the outage detection time that can be only partially solved via a list of all the systems featuring an automatic report device. In these cases, the Time Window would shrink to a few minutes and thus limit the number of Correlated Strikes. In addition, the list of systems using the same power source on some airports and the list of systems featuring forms of protection against lightning strikes would also improve the overall precision.

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