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First Cloud-to-Ground Lightning Timing Study

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December 2013

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Executive Summary

Customers: Launch Services Program (LSP) and Ground Systems Development and Operations (GSDO)

NASA's LSP, GSDO and other programs use the probability of cloud-to-ground (CG) lightning occurrence issued by the 45th Weather Squadron (45 WS) in their daily and weekly lightning probability forecasts. These organizations use this information when planning potentially hazardous outdoor activities, such as working with fuels, or rolling a vehicle to a launch pad, or whenever personnel will work outside and would be at-risk from lightning. These organizations would benefit greatly if the 45 WS could provide more accurate timing of the first CG lightning strike of the day. The Applied Meteorology Unit (AMU) has made significant improvements in forecasting the probability of lightning for the day, but forecasting the time of the first CG lightning with confidence has remained a challenge.

To address this issue, the 45 WS requested the AMU to determine if flow regimes, wind speed categories, or a combination of the two could be used to forecast the timing of the first strike of the day in the Kennedy Space Center (KSC)/Cape Canaveral Air Force Station (CCAFS) lightning warning circles. The data was stratified by various sea breeze flow regimes and speed categories in the surface to 5,000-ft layer. The surface to 5,000-ft layer was selected since that is the layer the 45 WS uses to predict the behavior of sea breeze fronts, which are the dominant influence on the occurrence of first lightning in Florida during the warm season. Due to small data sample sizes after stratification, the AMU could not determine a statistical relationship between flow regimes or speed categories and the time of the first CG strike. . As expected, although the amount and timing of lightning activity varies by time of day based on the flow regimes and speed categories, there are extended tails of low lightning activity making it difficult to specify times when the threat of the first lightning flash can be avoided. However, the AMU developed a graphical user interface with input from the 45 WS that allows forecasters to visualize the climatological frequencies of the timing of the first lightning strike. This tool should contribute directly to the 45 WS goal of improving lightning timing capability for its NASA, US Air Force and commercial customers.

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1. Introduction

NASA's Launch Services Program (LSP) and Ground Systems Development and Operations (GSDO) program along with other programs use the probability of cloud-to-ground (CG) lightning occurrence issued by the 45th Weather Squadron (45 WS) in their daily and weekly lightning probability forecasts. These forecasts are important in the warm season months, May-October, when the area is most affected by lightning. This study is restricted to the warm season because most of the lightning in Florida occurs then, and lightning activity in Florida in the summer is driven primarily by heating of the land by the Sun and has a strong repeatable diurnal behavior. As a result, it is reasonable to expect a tool to predict the timing can be created. The timing of lightning during the cool season is much less challenging since it is associated with approaching weather fronts, which can be predicted fairly well by numerical weather prediction models. In addition, the amount of lightning is much less in Florida during the cool season. LSP, GSDO and other programs use this information when planning potentially hazardous outdoor activities, such as working with fuels, or rolling a vehicle to a launch pad, or when people will be working outside and at-risk from lightning. These organizations would benefit greatly if the 45 WS could provide more accurate timing of the first CG lightning of the day in addition to the probability of lightning occurrence. The AMU has made significant improvements in forecasting the probability of lightning for the day (Lambert and Wheeler 2005; Lambert 2007; Crawford 2010; Crawford and Bauman 2012). However, forecasting the time of the first CG lightning is still difficult.

For this task, the 45 WS requested the AMU to stratify the data by sea breeze flow regimes and speed categories in the surface to 5,000-ft layer, both defined in the 45 WS Forecast Reference Notebook (FRN), along with some alternate stratifications if the sample size from the original stratifications did not have enough samples to allow statistical comparison. The surface to 5,000-ft layer was selected since that is the layer the 45 WS uses to predict the behavior of sea breeze fronts, which are the dominant influence on the occurrence of first lightning in Florida during the warm season. The 45 WS also requested a graphical user interface (GUI) displaying the frequencies and percentages of the timing of lightning under the various stratifications. The AMU found no statistically significant differences among the various stratifications, but the 45 WS determined that a GUI would still be helpful to the forecasters and Launch Weather Officers (LWOs) to visualize patterns in the stratified data and provide useful guidance to the launch customers.

2. Data

The data used in this task were from the 45th Space Wing CG component of the Four Dimensional Lightning Surveillance System (4DLSS) and the 1000 UTC Cape Canaveral Air Force Station (CCAFS) soundings (XMR). The CG component of 4DLSS is better known by its previous name, the CG Lightning Surveillance System (CGLSS), therefore, that term will be used hereafter in this report. The period of record (POR) is 1989-2011 or the warm-season months of May-October. Note that CGLSS began reporting strokes rather than flashes in April 2008. Flash data was used in this study prior to 2008 and stroke data was used from 2008 to 2011. The difference between using first flash and first stroke would be fractions of a second apart and are thus inconsequential for the scope of this study. The AMU has the processed XMR and CGLSS data from previous tasks and used them to create distributions of time of the first CG strike in the KSC/CCAFS 5 NM lightning warning circles (Figure 1).

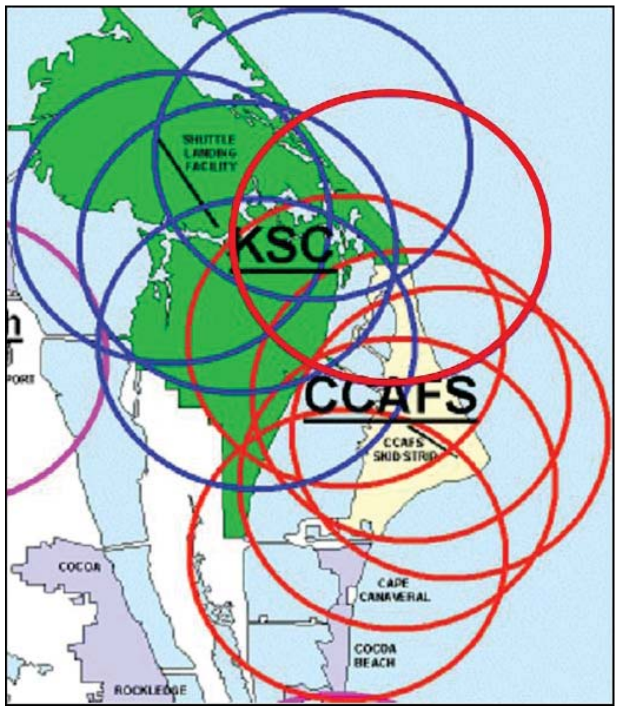


Figure 1. The 5-NM lightning warning circles on Kennedy Space Center KSC (blue) and CCAFS (red) (Crawford, 2010).

2.1 CGLSS

CGLSS is a network of six sensors that detects CG strokes on KSC/CCAFS and the surrounding area. It reports the date, time, latitude, longitude, peak current, polarity, and location error ellipse information of each detected stroke. The AMU has the processed the CGLSS data for previous tasks to include CG strikes that occurred in the KSC/CCAFS warning circles (Figure 1) for which the 45 WS has forecasting responsibility and for times between 0700 and midnight local time and are covered in the daily planning forecast issued by 45 WS. The CGLSS data were further filtered using Microsoft Access to capture the hour of the first lightning strike of the day after 0700 local time.

2.2 1000 UTC XMR Soundings

The AMU filtered the 1000 UTC XMR data to only include observations between the surface and 700 mb (~10,000 ft). According to the 45 WS FRN, the forecasters use the average direction in a sea breeze layer from the surface to 5,000 ft. The AMU used Microsoft Access to filter the data further to include only data in this sea breeze layer. The average surface to 5,000-ft winds were then calculated and used to determine the sea breeze flow regime of the day.

3. Stratification

The AMU and 45 WS held a meeting to discuss ways of stratifying the data into sea breeze flow regimes and speed categories. The 45 WS requested the AMU make an attempt to stratify the data by sea breeze flow regime for the surface to 5,000-ft layer and the speed regime, both as outlined in the 45 WS FRN. Some simplified stratification methods were also discussed in case there were not enough data in one or more of the stratification methods to create robust statistics in determining a relationship between the flow regime/speed stratifications and the time of the first CG strike. Table 1 shows the eight sea breeze flow regimes as defined in the FRN. Table 2 shows the alternated two- and four-sector sea breeze flow regimes that would be used if there were not enough data in the eight-sector stratifications. Table 3 shows the four-speed stratifications, and the alternate three-speed stratifications that would be used if there were not enough data in the four-speed stratifications. These speed ranges are based on the values in the 45 WS FRN that define different speed stratifications for each sea breeze flow regime.

Table 1. The eight 45 WS sea breeze flow regime sectors in the surface to 5,000-ft layer as defined in the 45 WS FRN.

Sea Breeze Flow Regime	***Direction Sector***
East (E)	>66º and ≤110º
Southeast (SE)	>110º and ≤155º
South	>155º and ≤200º
Southwest (SW)	>200º and ≤245º
West	>245º and ≤290º
Northwest (NW)	>290º and ≤335º
North	>335º or ≤20º
Northeast (NE)	>20º and ≤66º

Table 2. The alternate two- and four-sector sea breeze flow regimes for the surface to 5,000-ft layer.

Stratification	***Sea Breeze Flow Regime***	***Direction Sector***
Two-Sector	Off-Shore	≥135º and <315º
	On-Shore	≥315º or <135º
Four-Sector	Off-Shore SW	≥135º and <225º
	Off-Shore NW	≥225º and <315º
	On-Shore NE	≥315º or <45º
	On-Shore SE	≥45º and <135º

Table 3. The mean surface to 5,000-ft layer four-speed stratifications and alternate three-speed stratifications.

# Speed Stratifications	***Stratification Name***	***Wind Speed Range***
Four (FRN)	Low	≤5 kt
	Medium	>5 kt and ≤11 kt
	Medium High	>11 kt and ≤16 kt
	High	>16 kt
Three (alternate)	Low	≤7.7 kt
	Med	>7.7 kt and ≤12.6 kt
	High	>12.6 kt

4. Data Analysis

The AMU analyzed the stratified data sets described above to determine if there was a relationship between any of the flow regime/speed combinations and the timing of the first lightning strike of the day. In most cases, the analysis showed that stratification to the requested levels resulted in sample sizes that were too small for meaningful statistical analysis. Accordingly, the AMU performed analysis on data stratified by either the flow regimes in Table 1 and Table 2 or the speed stratifications in Table 3, but not combined.

4.1 Chi square (χ^2) Test

The AMU used the chi-square (χ^2) statistical significance test to determine whether there was a significant relationship between the time of the first lightning strike of the day and any of the sea breeze flow regimes or speed stratifications. The χ^2 test requires a null hypothesis (H_0), which is that no significant relationship exists between the flow regimes or speed categories and the first lightning strike of the day. H_0 can either be rejected as being improbable or not rejected. Note that H_0 is never accepted, just not rejected. Not rejecting H_0 means there is not enough evidence to reject the hypothesis; it does not mean that the hypothesis is valid. The alternative hypothesis (H_1) is that there is a significant relationship between the flow regime sectors or speed categories and the first lightning strike of the day.

For the first step in the χ^2 test, the AMU determined the observed number of strikes in each hour for each stratification and, from the observed values, calculated the associated expected number of strikes. The expected number of strikes was calculated by multiplying the number of strikes in each hour by the number of strikes in a flow regime sector or speed category regardless of time, then dividing that number by the total number of first lightning strikes of the day in the POR. For example, the total number of first strikes in the eight-sector easterly (E in Table 3) flow regime over all hours was 64. The total number of first strikes in the 0700 local hour was 35. These two values were multiplied and then divided by the total number of first strikes of the day over all hours and flow regimes for the POR, which 1,282. The expected number of first strikes for the 0700 local hour in the E flow regime was (64*35)/ 1282 = 1.75. This essentially assumes the distribution of first strikes is random, which is the same as assuming there is no significant influence from the flow regimes or speed categories. While it is not possible to have a fractional number of first strikes, this expected value, 1.75, is what was needed for the χ^2 calculation. The observed number of first strikes for this stratification was 5.

After all expected frequencies were calculated, the χ^2 statistic was calculated using the equation

$$\chi^2 = \Sigma \frac{(\#Observed - \#Expected)^2}{\#Expected} \text{ (Wilks 2006).}$$

The degrees of freedom of the χ^2 statistic is (r-1)*(c-1), where r is the number of rows and c is the number of columns in the contingency table. Following from the example above, the number of rows is equal to 17, since the data are consolidated by hour and there are 17 hours for each day in the dataset (0700-2300 local time). The hour designation is the start of the hour. For example 0700 signifies the time between 0700 and 0800 and 2300 signifies the time between 2300 and 0000. The number of columns for the 45 WS sea breeze flow regime sectors is 8. The degrees of freedom in this case is (17 – 1)*(8 – 1) = 112.

Then the AMU compared the calculated χ^2 statistic to an associated χ^2 critical value in a standard χ^2 distribution table using the α = 0.05 level of significance. If the calculated χ^2 statistic was greater than the χ^2 critical value, then H_0 was rejected with the assumption that there was a significant relationship between the first strike of the day and flow regime or speed category. Otherwise, if the statistic was less than the critical value and H_0 could not be rejected, it could be concluded with some certainty that there was no statistically significant relationship between the first strike of the day and flow regime or speed category.

Table 4 shows the overall results of the analysis. The only statistically significant outcome in which H_0 could be rejected was for the two-sector flow regimes (Table 2). For the χ^2 test to give accurate results, most expected values must be large. Dixon and Massey (1983) define this as no more than 20% of the expected values being < 5. Based on this restriction, the χ^2 test was invalid for the eight- and four-sector flow regime stratifications. All stratifications (either flow regime or speed category) that divided the data into more than two groups caused the resulting datasets to be too small for meaningful statistical analysis such that H_0 could not be rejected.

Table 4. Results from the χ^2 tests. H_0 is the null hypothesis indicating no significant statistical relationship between the first strike of the day and flow regime or speed category stratifications. H_1 is the alternate hypothesis indicating a significant statistical relationship between the first strike of the day and flow regime or speed category stratifications.

Stratification	***Status***	***Comments***
Eight-sector flow regimes (Table 1)	χ^2 test invalid	More than 20% of expected values < 5
Two-sector flow regimes (Table 2)	Reject H_0	Significant relationship with first strike (p-value = 0.000)
Four-sector flow regimes (Table 2)	χ^2 test invalid	More than 20% of expected values < 5
Four-speed categories (Table 3)	Fail to reject H_0	No relationship to first strike found (p-value = 0.081)
Three-speed categories (Table 3)	Fail to reject H_0	No relationship to first strike found (p-value = 0.312)

4.2 Marascuilo Procedure

Even though the χ^2 test showed a statistically significant relationship with the two-sector flow regimes, i.e. there are differences in the first lightning strike occurrence between onshore and offshore flow, the χ^2 test does not show which time period or periods caused the difference. In order to test which times were different, the AMU used the Marascuilo procedure (NIST/SEMATECH 2013). The Marascuilo procedure performs comparisons between all pairs of time periods simultaneously and can identify the times likely responsible for rejecting H_0.

To start the Marascuilo procedure, The AMU counted the number of hours for which data were available for the onshore and offshore stratifications. There were 17 hours each of onshore and offshore flow, equaling 34 time periods. The total number of pairs of data to compare was calculated using the formula r*(r-1)/2, where r is the number of groups of data, in this case 34. The total number of data pairs in this test was 34*33/2 = 561. This results in the absolute difference of the proportion of the first lightning strike occurrence between onshore and offshore flow at every time period being compared to the first lightning strike occurrence between onshore and offshore flow at every other time period. The absolute values of these differences are the test statistics. The next step was to pick a significance level (0.05) and compute the corresponding critical values for each pairwise comparison of proportions using the following formula.

$$\text{Critical Range} = \sqrt{\chi_U^2}\sqrt{\frac{p_i(1-p_i)}{n_i}+\frac{p_k(1-p_k)}{n_k}}$$

Where p_i is the proportion of the first lightning strike occurrence in a particular hour and flow regime, p_k is the proportion of the first lightning strike occurrence in a different hour and flow regime, n_i and n_k are the counts of occurrences of the first lightning strike occurrence in a particular hour and flow regime for the POR, and χ^2_U is the upper tail critical value of the chi-square distribution having r-1 (33) degrees of freedom. If the absolute difference in the data pair was greater than its critical range, then it could be concluded that observed values were significantly different from each other (Levine et al. 2007).

Unfortunately, the Marascuilo procedure did not find any observed values that were significantly different from one another, mostly likely due to the small group sizes after stratification by hour as needed for the procedure.

5. Graphical User Interface

Although the number of observations in each of the stratifications was too small to determine relationships to the first lightning strike of the day, the AMU asked the 45 WS if providing a GUI displaying the frequencies and percentages of the timing of lightning under the various stratifications would be helpful. The 45 WS agreed that such a GUI would be helpful to the forecasters and LWOs in generating their daily forecasts for lightning timing. The 45 WS LWOs also requested that a Thompson Index (TI) stratification be added to the GUI to account for stability and moisture. In previous AMU studies (Lambert 2005, Lambert 2007, Crawford 2010, Bauman and Crawford 2012), TI was an important predictor of lightning occurrence for most of the warm season months. The TI stratification thresholds in the GUI were adapted from Vasquez (2006) and are shown in Table 5. The GUI displays the climatological statistics for the times of the first lightning strike of the day in each month, flow regime direction, wind speed category and TI stratification.

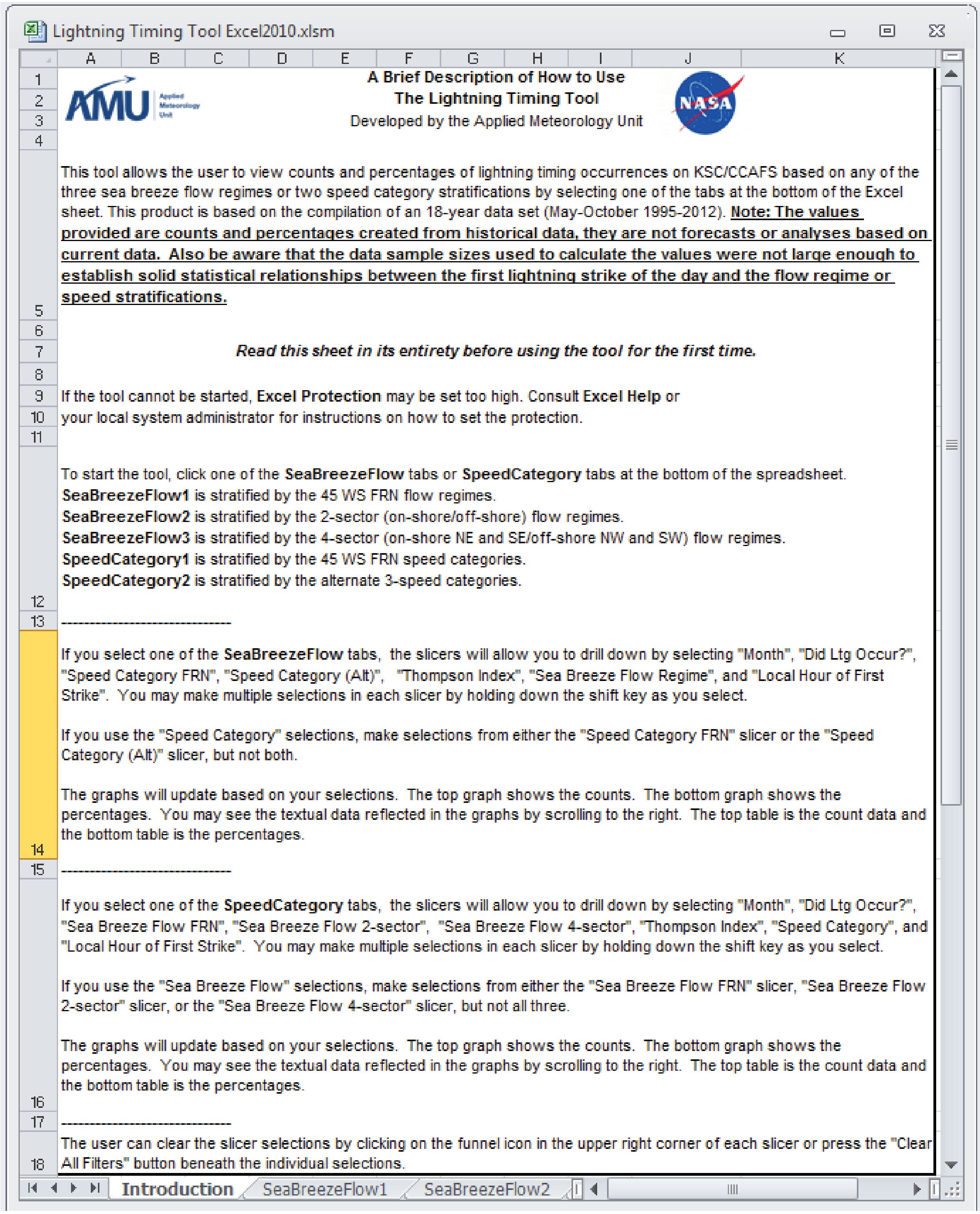
Table 5. TI thresholds adapted from Vasquez (2006).

TI	*Description*
<25	No thunderstorm
≥25 to <34	Potential of thunderstorms
≥35 to <40	Potential of thunderstorms approaching severe
≥40	Potential of severe thunderstorms

5.1 Excel Workbook

The GUI was developed using the slicers feature in Excel 2010. Slicers, which are new to Excel 2010, are embedded graphic objects that allow the user to quickly and easily filter data in an Excel PivotTable using multiple criteria. Slicers can also be used to filter data in more than one PivotTable created in the workbook simply by connecting additional tables. Slicers show which filtering criteria are currently selected in the connected PivotTables (Harvey 2010). The 45 WS LWOs and forecasters provided input to the final design of the GUI to make sure it met their operational needs.

The Excel workbook with the GUI contains six worksheets. The first worksheet is the Introduction worksheet. It is displayed automatically upon opening this Excel file and contains a brief description of how to use the lightning timing GUI. It also emphasizes to the user that the sample sizes were small so the data should be used for visualization only and not for making statistically based predictions. Figure 2 shows the Introduction worksheet. The next three worksheets contain the PivotTable slicers for the three sea breeze flow regime stratifications discussed in Section 3. The last two worksheets contain the PivotTable slicers for the two speed category stratifications also discussed in Section 3.


Lightning Timing Tool Excel2010.xlsm

A Brief Description of How to Use
The Lightning Timing Tool
Developed by the Applied Meteorology Unit

This tool allows the user to view counts and percentages of lightning timing occurrences on KSC/CCAFS based on any of the three sea breeze flow regimes or two speed category stratifications by selecting one of the tabs at the bottom of the Excel sheet. This product is based on the compilation of an 18-year data set (May-October 1995-2012). **Note: The values provided are counts and percentages created from historical data, they are not forecasts or analyses based on current data. Also be aware that the data sample sizes used to calculate the values were not large enough to establish solid statistical relationships between the first lightning strike of the day and the flow regime or speed stratifications.**

Read this sheet in its entirety before using the tool for the first time.

If the tool cannot be started, **Excel Protection** may be set too high. Consult **Excel Help** or your local system administrator for instructions on how to set the protection.

To start the tool, click one of the **SeaBreezeFlow** tabs or **SpeedCategory** tabs at the bottom of the spreadsheet.
SeaBreezeFlow1 is stratified by the 45 WS FRN flow regimes.
SeaBreezeFlow2 is stratified by the 2-sector (on-shore/off-shore) flow regimes.
SeaBreezeFlow3 is stratified by the 4-sector (on-shore NE and SE/off-shore NW and SW) flow regimes.
SpeedCategory1 is stratified by the 45 WS FRN speed categories.
SpeedCategory2 is stratified by the alternate 3-speed categories.

If you select one of the **SeaBreezeFlow** tabs, the slicers will allow you to drill down by selecting "Month", "Did Ltg Occur?", "Speed Category FRN", "Speed Category (Alt)", "Thompson Index", "Sea Breeze Flow Regime", and "Local Hour of First Strike". You may make multiple selections in each slicer by holding down the shift key as you select.

If you use the "Speed Category" selections, make selections from either the "Speed Category FRN" slicer or the "Speed Category (Alt)" slicer, but not both.

The graphs will update based on your selections. The top graph shows the counts. The bottom graph shows the percentages. You may see the textual data reflected in the graphs by scrolling to the right. The top table is the count data and the bottom table is the percentages.

If you select one of the **SpeedCategory** tabs, the slicers will allow you to drill down by selecting "Month", "Did Ltg Occur?", "Sea Breeze Flow FRN", "Sea Breeze Flow 2-sector", "Sea Breeze Flow 4-sector", "Thompson Index", "Speed Category", and "Local Hour of First Strike". You may make multiple selections in each slicer by holding down the shift key as you select.

If you use the "Sea Breeze Flow" selections, make selections from either the "Sea Breeze Flow FRN" slicer, "Sea Breeze Flow 2-sector" slicer, or the "Sea Breeze Flow 4-sector" slicer, but not all three.

The graphs will update based on your selections. The top graph shows the counts. The bottom graph shows the percentages. You may see the textual data reflected in the graphs by scrolling to the right. The top table is the count data and the bottom table is the percentages.

The user can clear the slicer selections by clicking on the funnel icon in the upper right corner of each slicer or press the "Clear All Filters" button beneath the individual selections.

Introduction | SeaBreezeFlow1 | SeaBreezeFlow2

Figure 2. The GUI Introduction worksheet gives a brief description of how to use the lightning timing tool. This worksheet is automatically displayed when opening the Excel file.

5.2 Sea Breeze Flow Regime Stratifications

Error! Reference source not found. shows an example of the GUI with slicers from orksheet “SeaBreezeFlow1” (tab name at bottom of Figure 3) for the FRN sea breeze flow regime stratification (Table 1). Note that in this example, although the selection boxes for both the FRN speed and alternate speed categories (Table 3) are shown, the user is expected to select from one or the other, but not both. This aspect of the GUI is emphasized during customer training. The user can clear the slicer selections by clicking on the funnel icon in the upper right corner of each slicer or by pressing the “Clear All Filters” button below the slicer menus.

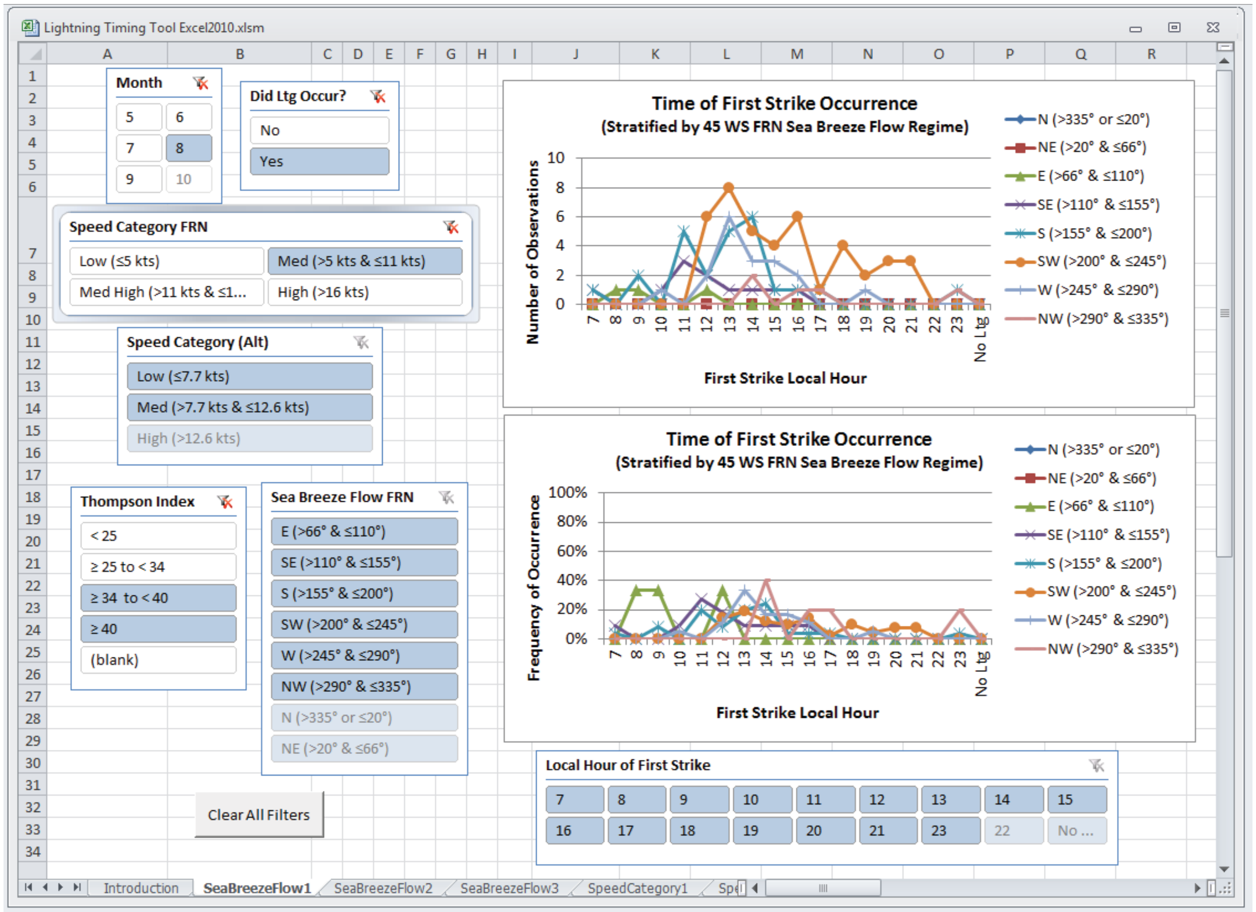


Figure 3. An example of the GUI using Excel 2010 slicers for the FRN flow regime stratification. In this example, the stratifications were the month of August, days when lightning occurred, medium FRN speed category, all speed categories, and Thompson Index ≥ 34. The top chart shows the number of times lightning occurred during each hour and the bottom chart shows the frequency of occurrence as a percentage of first lightning strike occurrences in each flow regime. Note that after the user selects the filters from the slicer menus, the categories that contain no data after filtering are grayed out and moved to the end of each of the slicer menus.

The user can see the tabular data in the PivotTables corresponding with the graphs by scrolling to the right of the graphs for the counts and to the right of the graphs and down for the percentages. Figure 4 and Figure 5 show examples of the counts and percentages corresponding to the example shown in Figure 3.

Lightning Timing Tool Excel2010.xlsm

Month	8
SpeedCategory1	Med (>5 kts & ≤11 kts)
SpeedCategory2	(All)
TI Bin	(Multiple Items)
LtgOccur	Yes

Count of First Strike by Local Hour	N (>335° or ≤20°)	NE (>20° & ≤66°)	E (>66° & ≤110°)	SE (>110° & ≤155°)	S (>155° & ≤200°)	SW (>200° & ≤245°)	W (>245° & ≤290°)	NW (>290° & ≤335°)	Grand Total
7	0	0	0	1	1	0	0	0	2
8	0	0	1	0	0	0	0	0	1
9	0	0	1	0	2	0	0	0	3
10	0	0	0	1	0	0	1	0	2
11	0	0	0	3	5	0	0	0	8
12	0	0	1	2	2	6	2	0	13
13	0	0	0	1	5	8	6	0	20
14	0	0	0	1	6	5	3	2	17
15	0	0	0	1	1	4	3	0	9
16	0	0	0	1	1	6	2	1	11
17	0	0	0	0	1	1	0	1	3
18	0	0	0	0	0	4	0	0	4
19	0	0	0	0	0	2	1	0	3
20	0	0	0	0	0	3	0	0	3
21	0	0	0	0	0	3	0	0	3
22	0	0	0	0	0	0	0	0	0
23	0	0	0	0	1	0	0	1	2
No Ltg	0	0	0	0	0	0	0	0	0
Grand Total	**0**	**0**	**3**	**11**	**25**	**42**	**18**	**5**	**104**

Introduction | SeaBreezeFlow1 | SeaBreezeFlow2 | SeaBreezeFlow3 | SpeedCategory1 | SpeedCategory2

Figure 4. An example of the tabular count data associated with the upper graph shown in Figure 3.

Lightning Timing Tool Excel2010.xlsm

Month	8
SpeedCategory1	Med (>5 kts & ≤11 kts)
SpeedCategory2	(All)
TI Bin	(Multiple Items)
LtgOccur	Yes

Count of First Strike by Local Hour	N (>335° or ≤20°)	NE (>20° & ≤66°)	E (>66° & ≤110°)	SE (>110° & ≤155°)	S (>155° & ≤200°)	SW (>200° & ≤245°)	W (>245° & ≤290°)	NW (>290° & ≤335°)	Grand Total
7			0.00%	9.09%	4.00%	0.00%	0.00%	0.00%	1.92%
8			33.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.96%
9			33.33%	0.00%	8.00%	0.00%	0.00%	0.00%	2.88%
10			0.00%	9.09%	0.00%	0.00%	5.56%	0.00%	1.92%
11			0.00%	27.27%	20.00%	0.00%	0.00%	0.00%	7.69%
12			33.33%	18.18%	8.00%	14.29%	11.11%	0.00%	12.50%
13			0.00%	9.09%	20.00%	19.05%	33.33%	0.00%	19.23%
14			0.00%	9.09%	24.00%	11.90%	16.67%	40.00%	16.35%
15			0.00%	9.09%	4.00%	9.52%	16.67%	0.00%	8.65%
16			0.00%	9.09%	4.00%	14.29%	11.11%	20.00%	10.58%
17			0.00%	0.00%	4.00%	2.38%	0.00%	20.00%	2.88%
18			0.00%	0.00%	0.00%	9.52%	0.00%	0.00%	3.85%
19			0.00%	0.00%	0.00%	4.76%	5.56%	0.00%	2.88%
20			0.00%	0.00%	0.00%	7.14%	0.00%	0.00%	2.88%
21			0.00%	0.00%	0.00%	7.14%	0.00%	0.00%	2.88%
22			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
23			0.00%	0.00%	4.00%	0.00%	0.00%	20.00%	1.92%
No Ltg			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Grand Total			**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

SeaBreezeFlow1 | SeaBreezeFlow2 | SeaBreezeFlow3 | SpeedCategory1 | SpeedCategory2

Figure 5. An example of the tabular percentage data associated with the lower graph shown in Figure 3.

The worksheets “SeaBreezeFlow2” and “SeaBreezeFlow3” are similar to worksheet “SeaBreezeFlow1” except the slicers use the two- and four-sector sea breeze flow regimes outlined in Table 2 rather than the FRN sea breeze flow regime sectors. The user can clear the slicer selections on these worksheets by clicking on the funnel icon in the upper right corner of each slicer or by pressing the “Clear All Filters” button below the slicer menus.

5.3 Speed Category Stratification

Error! Reference source not found. (from worksheet "SpeedCategory1") shows an xample of the GUI using slicers for the FRN speed category stratification (Table 3). Note that in this example, although the selection boxes for all three sea breeze flow regimes (Table 1 and Table 2) are shown, the user is expected to select from only one of the three sea breeze flow regime slicers. This aspect of the GUI is emphasized during customer training.

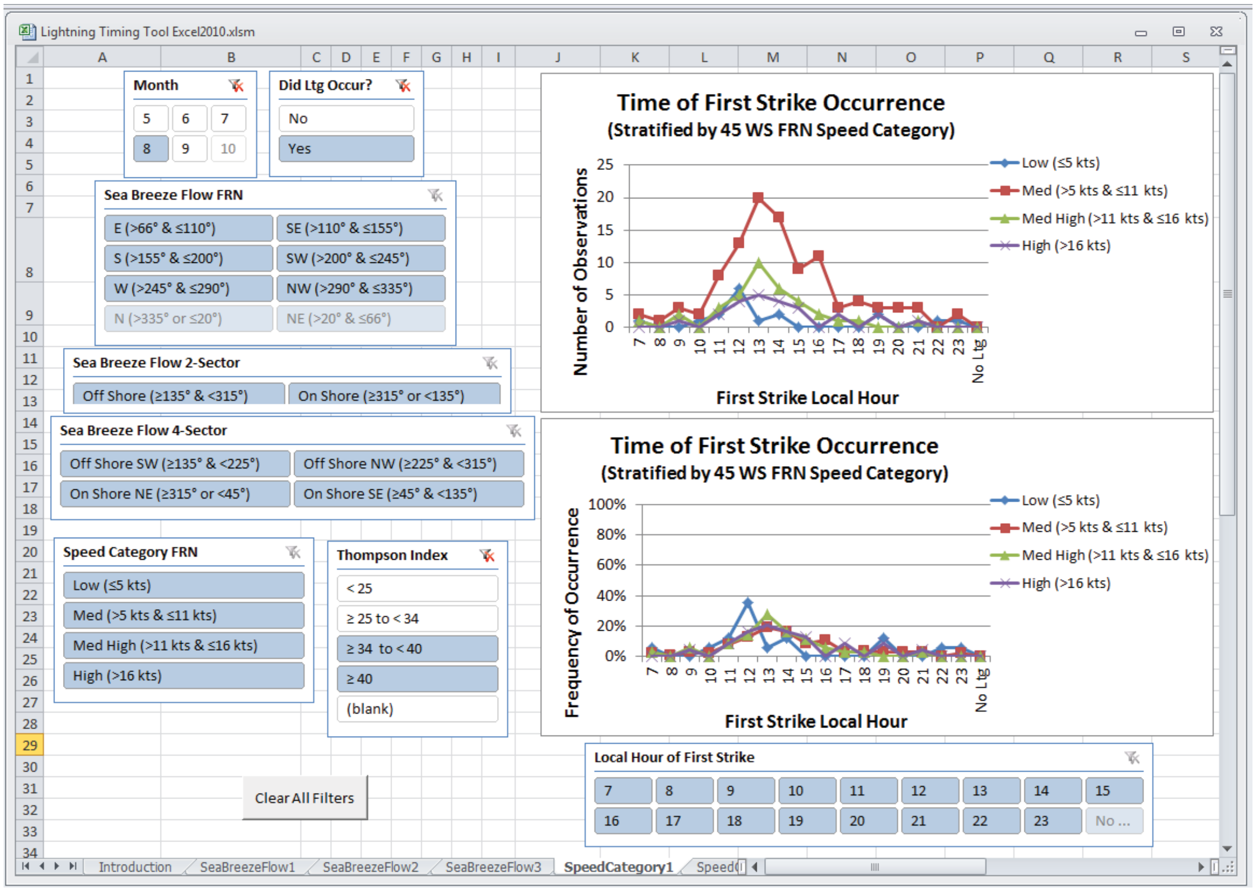


Figure 6. An example of the GUI using slicers for the FRN speed category stratification. In this example, the stratifications were the month of August, days when lightning occurred, all flow regimes, and Thompson Index ≥ 34. The top chart shows the number of times lightning occurred during each hour and the bottom chart shows the frequency of occurrence as a percentage of first lightning strike occurrences in each flow regime. Note that after the user selects the filters from the slicer menus, the categories that contain no data after filtering are grayed out and moved to the end of each of the slicer menus.

Similar to the flow regime example in Section 5.216, the user can see the tabular data, corresponding with the graphs by scrolling to the right of the graphs for the counts and to the right of the graphs and down for the percentages. The textual data is similar to that shown in Figure 4 and Figure 5. The worksheet "SpeedCategory2" is similar to worksheet "SpeedCategory1" except the slicers use the alternate three-speed category stratification outlined in Table 2 rather than the FRN four-speed category stratification. The user can clear the slicer selections on these worksheets by clicking on the funnel icon in the upper right corner of each slicer or by pressing the "Clear All Filters" button below the slicer menus.

6. Summary and Conclusions

NASA's LSP, GSDO, and other programs use the probability of CG lightning occurrence issued daily by the 45 WS when planning potentially hazardous outdoor activities, such as working with fuels, or rolling a vehicle to a launch pad, or when people will be working outside at-risk from lightning. While the AMU has made significant improvements in forecasting the probability of lightning for the day, forecasting the time of the first CG lightning is still difficult. LSP, GSDO, and other programs would benefit greatly if the 45 WS could provide more accurate timing of the first CG lightning of the day in addition to the probability of lightning occurrence.

To address this issue, the 45 WS requested the AMU to determine if flow regimes, wind speed categories, or a combination of the two could be used to forecast the timing of the first strike of the day. The AMU stratified the data by sea breeze flow regimes and speed categories in the surface to 5,000-ft layer as defined in the 45 WS FRN for sea breeze front behavior, along with some alternate stratifications. The 45 WS also requested a GUI displaying the frequencies and percentages of the timing of lightning under the various stratifications.

The AMU used the χ^2 test to determine if statistical relationships existed between the time of the first CG strike and flow regime and/or speed category. In most cases, the analysis showed that stratification to the requested levels resulted in sample sizes that were too small for meaningful statistical analysis. The only statistically significant outcome using the χ^2 test was for the two-sector flow regimes, meaning there were differences in the first lightning strike occurrence between onshore and offshore flow regimes. The χ^2 test did not show which time period or periods caused the difference. In order to test which times were different, the AMU used the Marascuilo procedure to perform comparisons between all time periods and onshore and offshore flow regimes simultaneously and identify the time periods and flow regimes likely responsible for the significant outcome. Again due to the small sample sizes, the Marascuilo procedure did not find any observed values that were significantly different from one another.

Even though the sample sizes were too small for meaningful statistical analysis, the AMU and 45 WS agreed that providing a GUI displaying the climatological frequencies and percentages of the timing of lightning under the various stratifications would be helpful to the forecasters and LWOs in generating their daily forecasts for lightning timing. The GUI displays the climatological statistics for the times of the first lightning strike of the day in each stratification month, flow regime sector, wind speed category, and TI. The AMU delivered the GUI to the 45 WS and they now use it in daily warm season operations. This tool should contribute directly to the 45 WS goal of improving lightning timing forecasts for its NASA, US Air Force and commercial customers.

It is possible more data from a longer POR would improve the statistics. However, because only the first lightning strike of the day is used, it will take a number of years to build the database, after stratifying, to the minimum number of observations required to test for statistical significance. In the meantime, the AMU is developing a locally tuned, high resolution mesoscale model for the Eastern Range. As part of that task, the AMU could look into implementing a lightning prediction algorithm that may lead to breakthroughs in predicting the timing of the first lightning strike of the day. It is also possible that a conditional climatology of lightning probability could be useful, e.g. given that one strike has been observed, what are the new probabilities for lightning at subsequent times. However, that will likely have even more problems with small sample size.

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List of Acronyms

4DLSS	Four Dimensional Lightning Surveillance System
45 WS	45th Weather Squadron
AMU	Applied Meteorology Unit
CCAFS	Cape Canaveral Air Force Station
CG	Cloud-to-Ground
CGLSS	CG Lightning Surveillance System
E	East
FRN	Forecast Reference Notebook
GSDO	Ground Systems Development and Operations
GUI	Graphical User Interface
H_o	Null hypothesis
H_1	Alternative hypothesis
KSC	Kennedy Space Center
LSP	Launch Services Program
LWO	Launch Weather Officer
N	North
NE	Northeast
NM	Nautical mile
NW	Northwest
POR	Period of Record
S	South
SE	Southeast
SW	Southwest
TI	Thompson Index
W	West
XMR	CCAFS rawinsonde 3-letter identifier
χ^2	Chi-squared

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14. ABSTRACT
The AMU was requested to determine if flow regimes, or wind speed categories could be used to forecast the timing of the first strike of the day in the Kennedy Space Center/Cape Canaveral Air Force Station lightning warning circles. Due to small data sample sizes the AMU could not determine a statistical relationship between flow regimes or speed categories and the time of the first lightning strike. However, the AMU developed a graphical user interface that allows forecasters to visualize the climatological frequencies of the timing of the first lightning strike.

15. SUBJECT TERMS
weather, meteorology, lightning, cloud-to-ground (CG) strike, first strike of the day, timing, statistical analysis, Kennedy Space Center, Cape Canaveral Air Force Station, Applied Meteorology Unit

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