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Using Timelines Of GPS-measured Precipitable Water In Forecasting Lightning At Cape Canaveral AFS and Kennedy Space Center

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1. Introduction

The 45th Weather Squadron (45 WS) is the U.S. Air Force unit that provides weather support to America's space program at Cape Canaveral Air Force Station (CCAFS) and Kennedy Space Center (KSC). The weather requirements of the space program are very stringent (Harms et al., 1999). In addition, the weather in east central Florida is very complex. This is especially true of summer thunderstorms. Central Florida is 'Lightning Alley', the area of highest lightning activity in the U.S. (Huffines and Orville, 1999). The 45 WS uses a dense network of various weather sensors to meet the operational requirements in this environment (Roeder et al., 2003).

One of the major duties of the 45 WS is forecasting lightning. This is done for several key activities. The 45 WS issues lightning advisories for 14 advisory circles of 5 nmi radius centered on key locations with considerable outdoor activity (Figure-1) (Weems et al., 2001). The lightning advisory circles have considerable overlap on CCAFS/KSC. The 45 WS uses a two-tier lightning advisory process. A Phase-1 Lightning Watch is issued for a lightning advisory circle(s) when lightning is expected in that circle(s) with a desired lead-time of 30 min. A Phase-II Lightning Warning is issued when lightning is imminent or occurring in that circle(s).

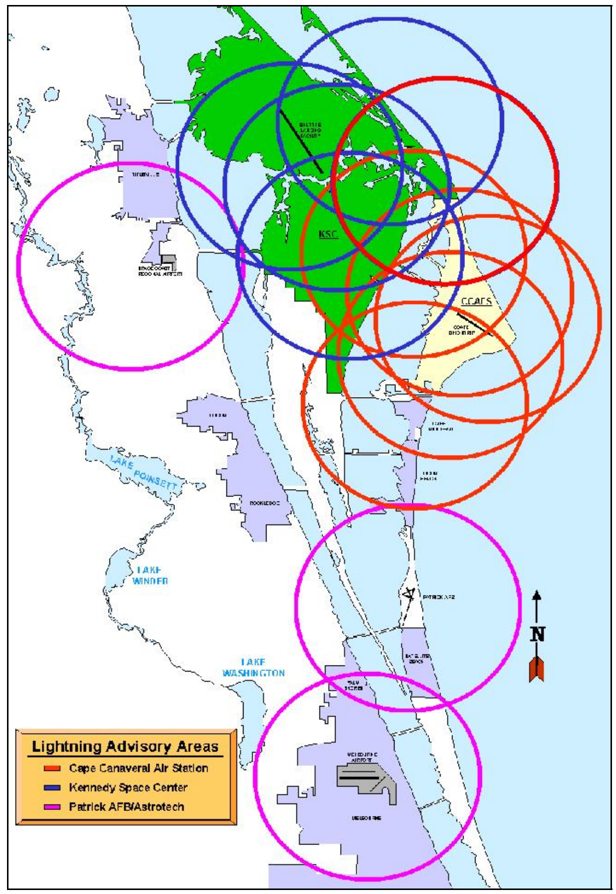

Figure-1. The 13 lightning warning circles used by 45 WS at the time of this study. Since then, a 14th warning circle has been added at the north end of KSC. Lightning inside the CCAFS (red) or KSC (blue) circles defined the event being predicted in this study.

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The 45 WS also forecasts lightning for outdoor activities such as rolling the Space Shuttle from the Vehicle Assembly Building to the launch pad (Harms et al., 1999). Finally, the 45 WS forecasts lightning for some of the Lightning Launch Commit Criteria, the weather rules to avoid natural and rocket triggered lightning to in-flight space launch vehicles (McNamara et al., 2010).

The 45 WS has developed several techniques to forecast lightning (Roeder and Pinder, 1998). A new technique being investigated is timelines of GPS-based Precipitable Water. This paper will summarize the results of this potential new lightning forecast technique.

2. GPS-Precipitable Water Background

The Global Position Satellites (GPS) can be used to calculate Precipitable Water (PW) over a location with accuracy better than radiosondes and updates as fast as 30 minutes. A high precision dual wavelength GPS antenna with a surface barometer is required.

PW is traditionally calculated from weather balloons. However, it was discovered nearly two decades ago that PW can be calculated from GPS satellites (Bevis et al., 1992; 1994). Previous researchers have called this GPS Integrated Water Vapor, but the authors use the term 'precipitable water', rather than Integrated Water Vapor, since the two terms are equivalent and precipitable water is the older and better established term. Applications of GPS-PW have been explored by Businger et al. (1996), Bauman et al. (1997), and Wolfe and Gutman (2000).

The phase delay of GPS signals passing through the atmosphere depends on the electron density in the ionosphere, the mass of the atmosphere, the amount of hydrometeors in the atmosphere, and the total amount of water vapor in the atmosphere. The delay due to the ionospheric electron density along each GPS line of sight can be calculated from the total electron count, which can be calculated by comparing the L1 and L2 GPS signals. The mass of the atmosphere can be calculated from the surface pressure measured by a barometer at the surface. The GPS phase delay due to hydrometeors is usually insignificant and not considered. Therefore, any GPS propagation delay remaining after accounting for these three delays is attributed to the total amount of water vapor along the line of sight from the GPS antenna and the GPS satellite. GPS-PW is normally measured by averaging the GPS propagation delays over all of the GPS satellites more than 15° above the horizon over a 30-min period.

GPS-PW has several important advantages over PW from weather balloons. GPS-PW is as accurate as weather balloons, if not more so. It is available every 30 min, as compared with twice a day, which is typical of weather balloons. GPS-PW provides a remote all-weather capability. GPS-PW tends to more representative of the vertical column over the antenna, as opposed to weather balloons that drift downwind. Finally, GPS-PW can be automated, thereby avoiding the costs of human-operated weather balloons.

3. GPS-PW in Lightning Forecasting

Previous research showed that timelines of GPS-PW can be used to forecast the onset of lightning at Cape Canaveral Air Force Station (CCAFS) and NASA Kennedy Space Center (KSC) in east central Florida (Mazany et al., 2002). This paper summarizes the most recent research previously reported in Kehrer et al. (2008).

Logistic regression equations were developed to forecast the probability of lightning at CCAFS/KSC for lead-times of 2-hr and 9-hr to support various operational requirements. The predictand is a lightning flash detected by the National Lightning Detection Network (NLDN) (Cummins, et al., 1998) inside the 45 WS lightning warning circles (Figure-1). The lead-times for the two forecast models were selected to support operational lightning watches with a desired lead-time of 0.5-hr and major operations lasting up to 7.5-hr. An extra 1.5-hr was added to both lead-times to allow for sensor dwell (0.5 hr), communication to the GPS-PW center (0.25 hr), and calculation of the GPS-PW, communication to 45 WS, and interpretation by the 45 WS forecaster (0.75 hr). Thus the 0.5 hr desired lead-time for lightning warnings became a 2-hr lead-time and the 7.5-hr lead-time for major operations became a 9-hr lead-time. The regression equations were developed and tested from 4-years of summer lightning seasons (May-Sep) at CCAFS/KSC (2000-2003).

Logistic regression has several advantages over linear regression for probability forecasting. Logistic regression is bounded by 0 and 1, and so cannot produce invalid probabilities < 0 or > 1 as can happen in linear regression. In addition, the logistic curve's S-shape is very flexible, allowing a nearly step-like or a nearly linear response of the predictand to the predictor variable. Finally, logistic regression allows for a binary categorical predictand, such as lightning-occurred and lightning-did-not-occur in the case.

The variables for the logistic regression equations were selected from 26 candidate predictor variables (Table-1). The GPS-PW data were from the Cape Canaveral Coast Guard GPS-PW sensor, which is actually located on CCAFS. The K-Index Predictor variables were selected from the candidate predictors with both forward/backward selection. In forward selection, the process begins with no variables, adds the variable that explains the most variance (if that variance

Table-1

The 26 candidate predictor variables. The units of GPS-PW are cm.

No.	Candidate Predictor Variable
1	K-Index*
2	GPS-PW (current)
3	GPS-PW (0.5 hr before current)
4	GPS-PW (1.0 hr before current)
5	GPS-PW (1.5 hr before current)
6	GPS-PW (2.0 hr before current)
7	GPS-PW (2.5 hr before current)
8	GPS-PW (3.0 hr before current)
9	GPS-PW (3.5 hr before current)
10	GPS-PW (4.0 hr before current)
11	GPS-PW (4.5 hr before current)
12	GPS-PW (5.0 hr before current)
13	GPS-PW (5.5 hr before current)
14	GPS-PW (0.0 hr before current)
15	GPS-PW (6.0 hr before current)
16	GPS-PW (6.5 hr before current)
17	GPS-PW (7.0 hr before current)
18	GPS-PW (7.5 hr before current)
19	GPS-PW (8.0 hr before current)
20	GPS-PW (8.5 hr before current)
21	GPS-PW (9.0 hr before current)
22	GPS-PW (9.5 hr before current)
23	GPS-PW (10.0 hr before current)
24	GPS-PW (10.5 hr before current)
25	GPS-PW (11.0 hr before current)
26	GPS-PW (11.5 hr before current)

* From the last available CCAFS RAOB, simulating the data that would be available to forecaster

explained is ≥ 5%). The next variable is then selected based on the most new variance explained, independent of the previous variable (if ≥ 5%). The process continues adding more variables one at a time until the next best variable would explain less than 5% additional new independent variance. Backward selection works in a similar way, except one starts with all candidate predictors and removes the variables one by one that explain the least new additional independent variance until the next predictor explains ≥ 5% variance. Since forward and backward selection can choose different predictor variables, the resulting logistic regression equations could have different performance. Indeed, different predictor variables were chosen for by the two selection methods for both the 2-hr and 9-hr forecast models. As a result, logistic regression equations were developed using both set variables for both models and the model with the best performance was chosen as the final model.

2.1 2-Hr Logistic Regression Equation

The final logistic equation for the 2-hr forecast model was selected based on which equation produced the best Operational Utility Index (OUI). The OUI is a non-standard performance metric developed by 45 WS for their lightning watches and warnings (D'Archangelo, 2000). Since the 45 WS lightning watches and warnings are so critical to personnel safety, Probability Of Detection (POD) is the most important performance metric, i.e. 45 WS is willing to trade some skill to get a higher POD since people lives are on the line. However, a good True Skill Statistic (TSS), a more traditional metric, is the second most important performance metric. Finally, a good False Alarm Rate (FAR) is considered third in importance. The 45 WS subjectively assigned a relative weight of 3 to POD, a weight of 2 to TSS, and a weight of -1 to FAR. The negative sign in the FAR weight accounts for FAR being an inverted performance metric where lower score is better. The sum of these three weighted parameters is then normalized by the sum of the absolute value of the weights. The OUI equation is as follows:

$$OUI = \frac{(3 * POD) + (2 * TSS) + (-1 * FAR)}{6}$$

Other performance metrics than OUI were considered in the selection of the final model to ensure the best overall choice was made. Those metrics were POD, FAR, TSS, and Hit Rate.

The final 2-hr regression equation used four predictor variables (Table-2). The three GPS-PW predictors selected all explained more independent variance than the K-Index, a widely used RAOB thunderstorm index and one of the most skillful RAOB indexes for predicting thunderstorms at CCAFS/KSC (Lambert and Roeder, 2008; Lambert et al., 2006; Kelly et al., 1998). This strongly suggests that GPS-PW can contribute significantly new and useful information to forecasting lightning at CCAFS/KSC.

Table-2

2-hr logistic regression equation predictor variables listed in order of statistical importance. No other candidate predictor variables were statistically significant.

Rank Order	Predictor
1	GPS-PW (0.5 hr)
2	GPS-PW (7.5 hr)
3	GPS-PW (current)
4	K-Index

The units of GPS-PW are cm.

The resulting 2-hr forecast equation is:

$$P(L) = \frac{1}{1 + e^{-(-2.366 + 2.053x1 - 0.538x2 + 0.322x3 + 0.031x4)}}$$

where P(L) = probability of lightning,
x1 = GPS-PW (0.5 hr),
x2 = GPS-PW (7.5 hr),
x3 = GPS-PW (current), and
x4 = K-Index.

The authors speculate that the meteorological explanation for the variables selected is as follows. The GPS-PW (0.5 hr) predictor (change of GPS-PW over the previous half hour) likely represents moisture convergence as a thunderstorm is forming. Indeed, detecting this mechanism was the original inspiration by one of the authors (Roeder) for using timelines of GPS-PW in local lightning forecasting. The mechanism behind the GPS-PW (7.5 hr) predictor is unclear. Possibilities include general convergence over the FL peninsula due to solar heating (sunrise to thunderstorm formation typically at 2000 UTC is about 8 hours), or perhaps a dynamic trigger in the upward motion in the right-entrance and left-exit regions of weak jet streaks over the forecast area (Uccellini and Kocin, 1987), or moisture convergence under flow with a southerly component, or other mechanisms. The GPS-PW (current) variable likely represents the basic need of thunderstorms for moisture. Likewise, the least important variable, K-Index, likely represents the basic need of thunderstorms for instability and moisture.

2.2 9-Hr Logistic Regression Equation

The final logistic equation for the 9-hr forecast model was selected based on which produced the best TSS, which is a more traditional performance metric in meteorology. In addition, other performance metrics considered to ensure the best overall choice was made. Those metrics were POD, FAR, and Hit Rate. The OUI was calculated but not considered since the emphasis on personnel safety is less urgent in the longer range forecast since a lightning warning would also be issued for that operation if needed, which would cover the personnel safety requirement.

The final 9-hr regression equation used five predictor variables (Table-3). The four GPS-PW predictors selected all explained more independent variance than the K-Index, again strongly suggesting that GPS-PW can contribute significantly new and useful information to forecasting lightning at CCAFS/KSC.

Table-3

9-hr logistic regression equation predictor variables listed in order of statistical importance. No other candidate predictor variables were statistically significant.

Rank Order	Predictor
1	GPS-PW (current)
2	GPS-PW (8.5 hr)
3	GPS-PW (3.5 hr)
4	GPS-PW (12.0 hr)
5	K-Index

The units of GPS-PW are cm.

The resulting 9-hr forecast equation is:

$$P(L) = \frac{1}{1 + e^{-(-4.885 + 0.541x1 - 0.446x2 + 0.346x3 + 0.235x4 + 0.071x5)}}$$

where P(L) = probability of lightning,
x1 = GPS-PW (current),
x2 = GPS-PW (8.5 hr),
x3 = GPS-PW (3.5 hr),
x4 = GPS-PW (12.0 hr), and
x5 = K-Index.

The authors speculate that the meteorological explanation for the variables selected is as follows. The

GPS-PW (current) likely represents the basic need of moisture for thunderstorm formation. The mechanism behind the GPS-PW (8.5 hr) predictor is unclear. Possibilities include general convergence over the FL peninsula due to solar heating (sunrise to thunderstorm formation typically at 2000 UTC is about 8 hours), or perhaps a dynamic trigger in the upward motion in the right-entrance and left-exit regions of weak jet streaks over the forecast area (Uccellini and Kocin, 1987), or moisture convergence under flow with a southerly component, or other mechanisms. The mechanism behind the GPS-PW (3.5 hr) predictor is also unclear, but may be due to approaching sea breeze fronts. The GPS-PW (12.0 hr) may be a mesoscale signal from a larger/longer scale phenomenon than the seas breeze, perhaps upward motion from right entrance/left exit quadrants of weak jet streaks overhead (Uccellini and Kocin, 1987). The K-Index represents the instability and moisture needed for thunderstorm formation.

A surprising result was the selection of the 12-hr change in GPS-PW. This was the largest time interval for change in GPS-PW in the candidate predictor variables. This suggests that change in GPS-PW for larger time intervals need to be considered to truly optimize the 9-hr regression equation.

2.3 Performance of the GPS-PW Lightning Prediction Models

The performance of the logistic regression equations was verified with randomly selected test data not used in the development of the equations. A random sample of 10% of the four summer seasons of available data were used (May-Sep 2000-2003).

The performance metrics will vary depending on which probability threshold is used to convert the forecast probabilities into yes/no categorical forecasts. The optimal probability threshold was chosen based on the OUI. The OUI was discussed in section-3. A threshold of 0.32 produced the best OUI for the 2-hr model. For the 9-hr model, TSS was used to pick the optimal probability threshold. A TSS of 0.36 yielded the best TSS for the 9-hr model. Since both of these thresholds are less than 0.50, this suggests these techniques have a positive bias. With these thresholds, the performance of the 2-hr and 9-hr regression equations is summarized in Table-4 and Table-5, respectively.

Even though the performance may not appear impressive, it appears that GPS-PW timelines provide useful new information for predicting thunderstorm formation not contained in other commonly used approaches.

Table-4

2-hr logistic regression equation performance on independent test data optimized for OUI with the 0.32 threshold optimized to convert the probability forecasts into yes/no forecasts.

POD	95%
FAR	48%
TSS	18%
OUI	45%

Table-5

9-hr logistic regression equation performance on independent test data optimized for TSS with the optimized 0.36 threshold to convert the probability forecasts into yes/no forecasts.

POD	81%
FAR	49%
TSS	34%
OUI	44%

3. Possible Future Work

Future work should include developing the GPS-PW timelines into an operational tool for use at CCAFS/KSC. This would include increased sample size, extending the changes in GPS-PW time interval beyond 12-hr in the 9-hr regression equation, looking for ways to reduce the high FARs while maintaining high PODs, stratification by the lightning flow regimes for central Florida, and developing and testing the technique for use under conditions with more synoptically driven thunderstorms. Performance verification more appropriate to probability forecasts should also be used, such as reliability/attributes diagrams, Brier Skill Score, Ratio Skill Score against other baseline forecast methods such as the 45 WS daily planning forecasts, sharpness diagrams, ROC diagrams, etc.

Researchers interested in developing the use of GPS-PW timelines for lightning prediction further for operational use at CCAFS/KSC are encouraged to contact the corresponding author.

4. Summary

GPS-PW and its timelines appear to be useful for forecasting lightning at CCAFS/KSC during the summer months with lead-times up to several hours. This technique should receive further research and assessment for implementation as an operational forecast technique.

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