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Recent Weather Support Improvement Initiatives By The 45th Weather Squadron

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1. INTRODUCTION

The mission of the 45th Weather Squadron (45 WS) is to 'exploit the weather to ensure safe access to air and space' at Cape Canaveral Air Force Station (CCAFS), NASA's Kennedy Space Center (KSC) and Patrick Air Force Base. The 45 WS provides comprehensive weather services for personnel safety, resource protection, pre-launch ground processing, day-of-launch, post-launch, aviation, and special operations. These services are provided for more than 30 space launch countdowns per year by the Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and commercial launch customers. Weather presents significant challenges to space lift and is the leading cause of countdown delayed and scrubbed launches.

The 45 WS mission is complicated by the extreme forecasting challenges along the central coast of Florida in the 'Thunderstorm Capital' of the U.S. (Figure 1). The most frequent warning products issued by 45 WS are for lightning and convective winds. Thunderstorm formation during the summer is dominated by numerous weak boundary layer interactions, including the sea breeze fronts from the Atlantic Ocean and the Gulf Of Mexico, the local Indian River and Banana River Breezes, convective outflows, horizontal convective rolls, and others (Figure 2). During the winter, the complex frictional and stability environment (Figure 3) complicates forecasting the boundary layer winds.

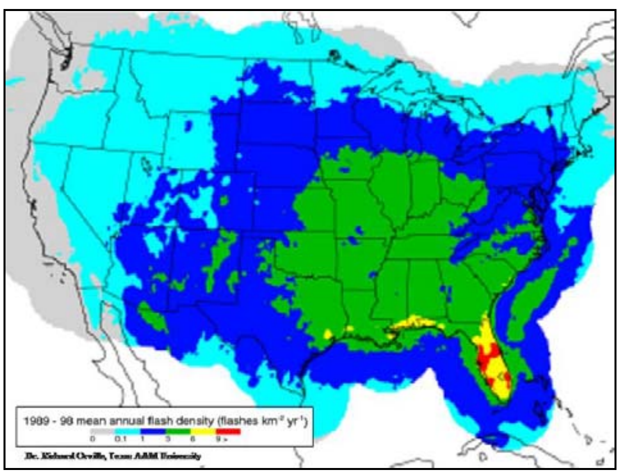

Figure 1. Average annual cloud-to-ground lightning flash density (1989–1998) based on NLDN data. (provided by Dr. Orville Texas A&M University).

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Due to these forecast challenges, the 45 WS participates in an active operational research program to meet our customers' many stringent and unusual forecasting requirements. This research focuses on the most important operational needs of the customers including lightning forecasting, lightning launch commit criteria, convective wind forecasting, forecasting of boundary layer peak winds in our cool season, and low temperature forecasting. The 45 WS also provides extensive climatological assistance to our customers.

Figure 2. Visible weather satellite image of a typical summer day in central Florida. Note the complex interactions between numerous low altitude boundaries.

Figure 3. Map of CCAFS/KSC area. Note the numerous land-water boundaries.

2. RECENT FORECAST IMPROVEMENT INITIATIVES

Several of the recent forecast improvement initiatives by 45 WS are presented below. The discussion for each topic will be brief. Readers interested in more detail on any of the following projects may contact the corresponding author (william.roeder@patrick.af.mil).

2.1 Anvil Lightning Launch Commit Criteria

The Lightning Launch Commit Criteria (LLCC) are a set of 12 rules to avoid natural and rocket triggered lightning to in-flight space launch vehicles (Roeder et al., 1999). An Airborne Field Mill experiment (Figure 4), including cloud physics sensors was conducted to improve the LLCC for anvil clouds and thick clouds (Dye et al., 2003) (Merceret and Christian, 2000). Data were collected during three periods in 2000 to 2001.

Figure 4. The research aircraft from the Airborne Field Mill Experiment.

Extensive analysis of that data since then produced two main changes to the LLCC. The radar definition for cloud edge was changed from 10 dBZ to 0 dBZ in 2003. This increased launch safety. In addition, two new LLCC for attached and detached anvil clouds were implemented in summer 2005. The main change in these new anvil LLCC was the ability to launch closer and sooner to and through anvil clouds if a certain radar condition is satisfied. This radar condition is a Vertically-Averaged Height Integrated Radar Reflectivity (VAHIRR). VAHIRR essentially averages the reflectivity of anvil clouds from cloud base at or above 0°C to cloud top over a ±3 NM box. If VAHIRR is less than 10 dBZ•Km within 3 NM along the launch path, then the above benefits may be realized. These new anvil LLCC should increase launch opportunity an estimated average of 30% under anvil conditions without compromising launch safety, as compared to the previous anvil LLCC, for an average savings of $75,000/year. The calculation of VAHIRR is quite complicated, with many stipulations. Full details are provided at Merceret et al. (2006).

Future improvements to the anvil LLCC from the airborne field mill experiment are likely. One study has shown that the electric fields outside of anvil clouds fall off with distance faster than previously believed (Ward and Merceret, 2004). This could lead to reducing the anvil standoff distances by up to a factor of two or three.

2.2. Local Lightning Probability Tool

The most frequent warning issued by 45 WS is for lightning. A new tool to predict the probability of lightning during the summer thunderstorm season (late May-early September) in the 45 WS lightning advisory areas was implemented in April 2005 (Lambert et al., 2005). This new tool considers the statistically most important indexes and other parameters from the local radiosonde, the lightning flow regime across the peninsula of Florida, the 24-hour persistence, and the daily climatology of lightning frequency (Table 1). A graphical user interface was developed for accuracy and ease of use. This new tool has 48% better skill than the previous tool.

This tool was developed by the Applied Meteorology Unit (AMU) and integrated the results from several research projects over the past few years including M.S. theses from the Air Force Institute of Technology, Florida State University, and local studies. The AMU is a contractor that provides technology and technique development, evaluation, and transition services to improve operational weather support to the Space Shuttle and the national space program (Bauman et al., 2004). This new tool performs very well and the 45 WS has tasked the AMU to pursue various improvements to the tool.

Table 1. Variables used in the new lightning probability tool, developed by the Applied Meteorology Unit.

VARIABLES USED IN THE AMU LIGHTNING PROBABILITY TOOL (1989-2003)

MAY	JUN	JUL	AUG	SEP
Thompson Index (K-Index – Lifted Index)	800-600 Mb Relative Humidity	Total Totals	K-Index	1-Day Persistence
Flow Regime	1-Day Persistence	1-Day Persistence	Flow Regime	Flow Regime
1-Day Persistence	Lifted Index	800-600 Mb Relative Humidity	Total Totals	800-600 Mb Relative Humidity
Daily Climatology	Flow Regime	Daily Climatology	Daily Climatology	Daily Climatology
500 Mb Temperature	Daily Climatology	Flow Regime	800-600 Mb Relative Humidity	Lifted Index
N/A	N/A	N/A	1-Day Persistence	N/A

- Variables are listed in order of importance in predicting the lightning probability
- The flow regime probability, 1-day persistence, and daily climatology were selected for all five months and the 800-600 Mb relative humidity was selected for four out of the five months
- Thirteen variables were considered for each month, but the rest were not statistically significant

2.3. Minimum Temperature Tool

The 45 WS developed a new procedure to predict minimum temperatures. This new tool was implemented during the winter of 2004-2005 (Roeder et al., 2005). This new procedure improved the accuracy of minimum temperature forecasts by 11°F over the old tool and improved the performance of the 45 WS low temperature advisories with a 42% more meeting desired lead-time and 29% decrease (better) in false alarm rate.

The new tool uses a 'first guess' forecast of the expected low temperature using a linear regression equation with the 1000-850 MB thickness as the predictor variable (Figure 5). The old tool used subjective estimates of the low temperature from the 1000-500 MB thickness.

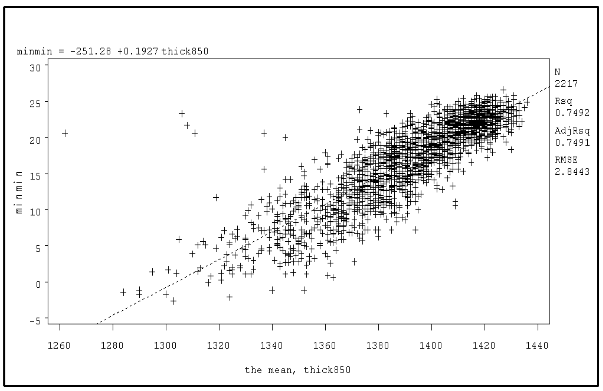


Figure 5. Scatter diagrams for the 1000-850 thicknesses versus the lowest minimum temperatures at 45 WS. Analysis and figures provided by the Air Force Combat Climatology Center.

A series of correction factors are then applied to the 'first guess' to produce the final minimum temperature forecast. The correction factors are based on wind speed, cloud cover and fog, wind direction, radiation inversion, low-level and mid-level humidity, and local surface dew point. The old tool had only a single subjective correction factor for one wind speed threshold. The new tool uses a best-fit power law regression instead (Figure 6). The old tool had only a single subjective correction factor for only a single cloud cover threshold. The new tool has eight categories and also adds fog. The low-level and mid-level humidity is a new correction factor for scattered to clear clouds. A new correction factor using the forecast minimum dew point is also used. The previous correction factors for surface temperature inversion and wind direction (on-shore/off shore flow) are maintained from the old tool. A Graphical Users' Interface was developed to increase accuracy and for ease of use.

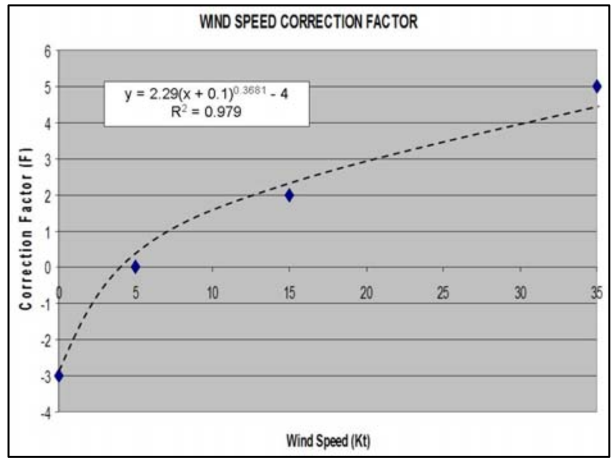


Figure 6. Best-fit power law for wind speed correction factor in the new 45 WS minimum temperature tool.

2.4. Downburst Tools

The second most frequent warning issued by 45 WS is for convective winds. The 45 WS began a convective winds project with Plymouth State University, NH in summer 2005 (Loconto et al., 2006). This project will update our downburst climatology, assess the performance of various Skew-T downburst indexes such as T1, T2, WIND Index, Microburst-Day Potential Index, Wet Microburst Severity Index, and the Synder Method. In addition, enhancements to the GOES sounder downburst products may be investigated, such as timelines at a point and isopleths at a single time. This project was funded under a NASA Space Grant.

Although the following techniques are not recent research, they are worth recapping here for readers who may not be familiar with this work. The 45 WS developed several downburst nowcasting techniques. The Echo Top/VIL Wind Gust Potential Chart provides the maximum wind gust expected given the Echo Top and VIL, as observed by radar. Research by an Air Force Institute of Technology (AFIT) student showed that using the same chart, but with Storm Top rather than Echo Top, provides 16% better accuracy and 29% better discrimination between 45 WS warning criteria (Figure 6) (Sullivan, 1999)). That research also found errors up to 11 Kt in the Air Force Weather Agency (AFWA) published Echo Top/VIL Chart, a finding that was cross-fed to AFWA for correction.

Another AFIT student found that a Weak Echo Trench or a Low Reflectivity Notch, which are vertical and horizontal protrusions of low reflectivity into the storm, respectively, indicates that a downburst is more likely (Mackay, 1998). These signatures may sound like the well known WER and BWER that are associated with severe weather, but these are different signatures associated with pulse thunderstorms in the Southeast U.S. in summer.

ST (kft) \ VIL (kg m^{-2})	15	20	25	30	35	40	45	50	55	60	65	70
60									18	27	33	39
55							14	24	31	37	42	46
50						19	28	34	39	44	48	52
45				11	22	30	36	41	45	49	53	57
40			14	24	31	37	42	46	50	54	57	61
35		15	25	31	37	42	46	50	54	58	61	64
30	13	24	31	37	42	46	50	54	57	61	64	67
25	22	29	35	41	45	49	53	57	60	63	66	69
20	27	33	39	43	48	52	55	59	62	65	68	71
15	30	36	41	46	50	53	57	60	63	66	69	72

Figure 6. The Storm Top/VIL Chart to estimate the maximum gust expected from individual radar cells. Using Storm Top provides significantly better performance than the previous Echo Top/VIL technique.

The AMU developed a technique using WSR-88D Cell Trends to predict the onset of downbursts (Wheeler, 1998) (Figure 7). They also co-developed with the 45 WS a new RAOB-based Microburst-Day Potential Index that predicts the likelihood of microbursts for that day based on vertical differences of equivalent potential temperature (Wheeler and Roeder, 1996) (Figure 8). At the same time, the AMU implemented the Wind Index developed by the National Severe Storms Forecast Center (now Storm Prediction Center) to predict the strongest downburst speed. The vertical difference in θ_e technique was cross-fed to AFWA and National Environmental Satellite, Data, and Information Service (NESDIS) where it is being used in their severe weather section, and as a GOES sounder product (Ellrod et al., 2000) (Figure 9), respectively.

If In One Volume-Scan
Hgt Max dBZ falls ≥ 8,000 Ft
(if initially ≥ 18,000 Ft)
AND
Cell-based VIL falls ≥ 10 Kg/m2
Then A Downburst Is Likely Beginning Aloft In
That Convective Cell

Figure 7. Cell Trends technique developed by the AMU to detect the onset of downbursts.

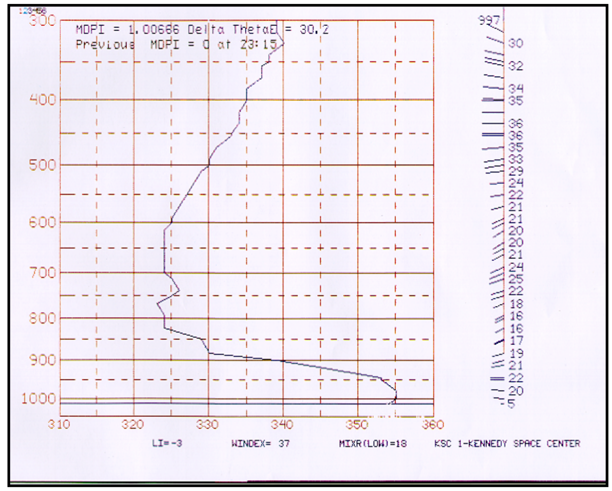


Figure 8. Microburst-Day Potential Index and Wind Index product at 45 WS. The vertical profile of θ_e is also provided since the level of minimum θ_e aloft is useful in other downburst techniques.

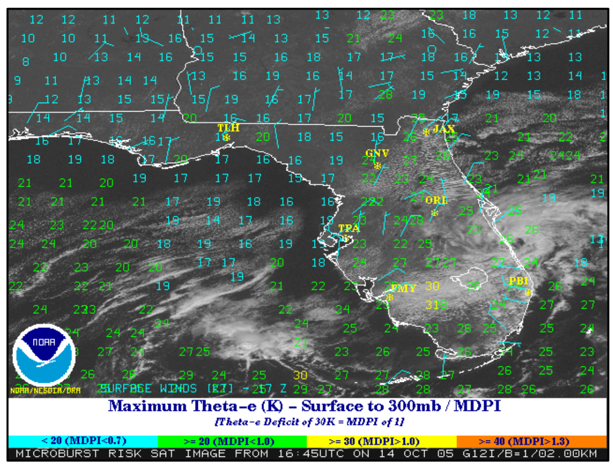
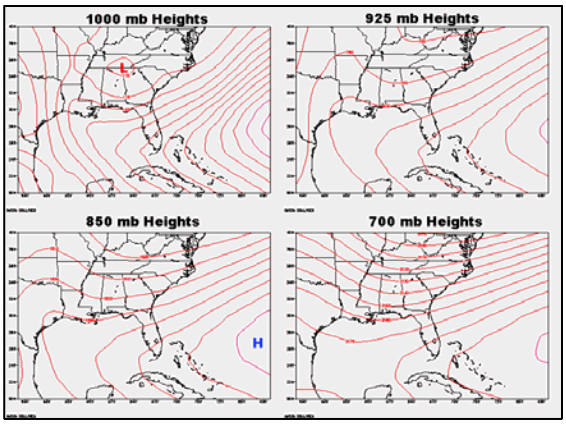


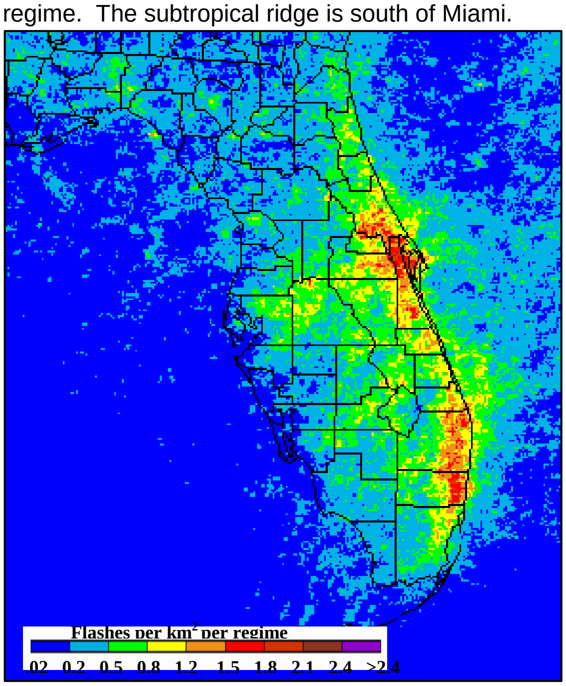
Figure 9. Sample of the Microburst-Day Potential Index product from the GOES sounder based on the technique developed by the 45 WS.

2.5. Flow Regime Lightning Probability

A climatology of lightning probability by flow regime within 20 NM of Kennedy Space Center and within 5 NM of Patrick AFB was created by an undergraduate intern from Pennsylvania State University during the summer of 2004. This was done to help support major ground processing operations, especially Space Shuttle rollout from the Vehicle Assembly Building to the launch pad and to supplement the 45 WS training program on Florida lightning flow regimes (Lericos et al., 2002). The pattern of lightning across the Florida peninsula during the summer is strongly influenced by the flow in the lower half of the atmosphere. The flow either accelerates/retards the inland penetration of sea breeze fronts from the Atlantic Ocean and the Gulf of Mexico and causes increased convergence and more thunderstorms on the other sea breeze front. Seven distinct flow regimes have been identified for the Florida Peninsula. For example, if southwest flow occurs over the Peninsula, such as with the subtropical ridge to the south, then the East Coast Sea Breeze front stays on the east side of the state and causes more thunderstorms there (Figure 10). This internship was funded by Kennedy Space Center.



a) Composite pressure charts for the southwest flow regime. The subtropical ridge is south of Miami.



b) Average cloud-to-ground lightning flash density for the southwest flow regime, based on NLDN data.

Figure 10. The Southwest lightning flow regime, which is one of the seven lightning flow regimes for Peninsular Florida (Lericos, 2002).

The same student returned for another internship during summer 2005 to update the daily lightning climatology within the 45 WS lightning warning areas to help update the lightning probability tool discussed in 2.2. This internship was funded by Pennsylvania State University.

This work used past data from the local cloud-to-ground lightning detection system (Boyd et al., 2004). This database was initially built by an Air Force Academy cadet in summer 2002 under their Cadet Summer Research Program. The 45 WS has found this database very useful and continues to update it to this day for the prospects of future research.

2.6. GPS-based Precipitable Water Lightning Forecast Tool

A new technique to forecast local lightning using timelines of precipitable water measured by Global Positioning Satellites (GPS-PW) is being investigated. The results have not been published yet, so more detail will be provided for this subtopic as compared to the other forecast initiatives.

A preliminary thesis was done at the University of Hawaii in 1999, which showed that the technique has promise (Mazany et al, 2002). A follow-on study was done with the University of Florida during early 2005. This study further verified the previous technique on independent data and developed two new operationally focused techniques for the 30-minute of desired lead-time of the 45 WS lightning advisories and the 6-8 hours of desired lead-time for major ground processing operations such as rollout of the Space Shuttle from the Vehicle Assembly Building to the launch pad. Allowing time for sensor dwell, communication, processing, and analysis by the forecaster time, the 30-minute and 6-8 hour forecasts for 45 WS operations become 2-hour and 9-hour forecasts when referenced to GPS-PW data time, respectively. The best combination of 26 candidate predictor variables was selected from the current GPS-PW, the latest K-Index from the CCAFS RAOB, and the change in GPS-PW in 30-minute intervals from 30 minutes to 12 hours (Table 2). It is interesting that in both cases, the K-Index, a traditional thunderstorm prediction tool, had the least contribution to the forecast while the non-traditional GPS-PW predictors had more contribution. After the optimal predictor variables were selected, then a logistic regression was performed for each of the two new tools. Next, the optimal logistic regression threshold was selected to optimize the forecast performance. The 2-Hour tool and the 9-Hour tool had an optimal logistic regression values of 0.32 and 0.37, respectively.

Table-2. Predictor variables statistically selected for the new GPS-PW lightning probability tools. Listed in order of contribution to the forecast.

TOOL	PREDICTORS
2-Hour	1) 0.5-hour ΔGPS-PW
	2) 7.5-hour ΔGPS-PW
	3) Current GPS-PW
	4) K-Index
9-Hour	1) Current GPS-PW
	2) 8.5-hour ΔGPS-PW
	3) 3.5-hour ΔGPS-PW
	4) 12-hour ΔGPS-PW
	5) K-Index

The 2-Hour tool was designed to optimize the Operational Utility Index (OUI). The OUI is a locally-developed composite performance metric that combines Probability Of Detection (POD), Kuiper Skill Score (KSS), and False Alarm Rate (FAR) with weights of three, two, and negative one, respectively. The OUI is then normalized by a divisor of six, so that perfect performance is an easily interpreted value of one.

$$OUI = \left[\frac{3(POD) + 2(KSS) - 1(FAR)}{6} \right]$$

These weights were selected based on professional judgment of the relative worth of the various metrics in the 45 WS lightning advisories. Optimizing on OUI was done since the 2-Hour tool was designed to support the 45 WS lightning advisories. Since the advisories are vital to personnel safety, more weight is given to POD and much less to FAR – issuing an unneeded lightning advisory is inconvenient in lost processing time and dollar costs, but missing a needed lightning advisory could cost lives.

The 9-Hour forecast tool was optimized on the more traditional KSS. This tool was designed to support major ground processing operations where fewer people are involved and they have fast access to shelter from lightning.

The performance of the original technique could not be duplicated as shown in Table 3. However, the two new techniques showed promise (Table 4). Further development is needed before this technique is ready for operational use. In particular, the high FAR needs to be reduced. Both the 2-Hour and the 9-Hour tools show a strong tendency to over forecast with biases of 1.47 and 1.54, respectively (1.0 = unbiased). This suggests a bias correction technique may prove useful. In addition, stratification by the lightning flow regimes for the Florida Peninsula, as discussed previously, may also prove useful in reducing the high FAR.

Table-3. Performance for the previous technique from the University of Hawaii for 1.5-Hour lightning forecasts. The promising performance in the original verification showed considerable reduction in this study.

Univ. Hawaii Model (1999)	POD	FAR	KSS
Original Performance	88.2%	30.1%	64.4%
New Verification	58.5%	75.6%	20.3%

Table-4. Forecast Performance for the two new GPS-based Precipitable Water lightning probability tools for independent verification data. The 2-Hour tool optimized OUI, while the 9-Hour tool optimized KSS.

TOOL	POD	FAR	KSS	OUI
2-Hour	94.6%	47.9%	0.184	0.454
9-Hour	80.2%	47.7%	0.356	0.293

2.7. Statistical Forecasting Of Lightning Cessation

A new approach to forecast the end of lightning is being explored. The NASA Faculty Fellowship Program funded a visiting scientist from Oral Roberts University during the summer of 2004 to investigate the 45 WS proposed statistical forecasting of lightning cessation. A climatological distribution of times between last and second-last flashes can provide general guidance on how long to wait after a candidate last lightning flash to achieve a desired level of low probability that it was indeed the last lightning. Also, a continually-updated best-fit decay curve of lightning flash rate in dying thunderstorms might be used to predict how long to wait until the probability of no more lightning reaches a desired level (Roeder and Glover, 2005). This proof-of-concept study showed that the approaches have good promise. Florida State University is beginning a Ph.D. dissertation in the summer of 2005 to further explore statistical forecasting of lightning.

3. SUMMARY

Some of the recent forecast improvement initiatives for the 45 WS were summarized. Seven topics were discussed (Table 5). Researchers interested in helping to improve weather support for America's space program are encouraged to contact the corresponding author to discuss opportunities.

Table-5. Forecast improvement initiatives discussed in this paper.

NO.	TOPIC
1	Lightning Launch Commit Criteria
2	Lighting Probability Forecasting
3	Minimum Temperature Tool
4	Downburst Prediction Tools
5	Lightning Probability Flow Regimes
6	GPS-PW Lightning Forecasting
7	Statistical Forecasting Of Lightning Cessation

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