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Weather research requirements to improve space launch from Cape Canaveral Air Force Station and NASA Kennedy Space Center

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1. Background

The 45th Weather Squadron (45 WS) is the United States Air Force unit that provides weather support to America's space program at Cape Canaveral Air Force Station (CCAFS), National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC), and Patrick Air Force Base. The Nations' space program is very sensitive to weather and has very stringent weather requirements (Harms et al., 1999) that range from conditions at the launch pad to the near-earth space environment. The risk due to violation of these weather criteria is the leading source of scrubs and delays to space launch. Weather is even more important during ground processing where thousands of people and billions of dollars in equipment are engaged to prepare the rockets, payloads, and launch pads in the weeks and months before space launch.

In addition to the space program's sensitivity to weather, the weather itself in east central Florida can be difficult to forecast. The phenomena that generate weather in this area can be very subtle and complex. This is especially true of summer thunderstorms, which are usually driven by collisions of many types of low-level boundaries. Florida is the 'Thunderstorm Capital' of the U.S. with the largest lightning flash density in the CONUS (Huffines and Orville, 1999) (Figure-1). Within Florida, the lightning activity concentrates across Central Florida, also known as 'Lightning Alley' (Figure-2). CCAFS/KSC lies at one end of 'Lightning Alley'.

The risk to launch operations due to the space environment also complicates weather support for several reasons. The precise impacts of the near-earth environment to a rocket and space vehicle are not fully understood, and there is limited ability to sense or model that vast environment. As a result, current support is limited to providing only rough approximations of risk.

To help meet the stringent terrestrial requirements of space launch and launch preparation in such a subtle meteorological environment, the 45 WS uses one of the most dense and diverse suite of weather sensors in operational meteorology. The suite of weather sensors is vital, but also represents a challenge since the weather community does not have decades of corporate experience in its use. This provides as complete a solution as possible, but there is still room for improvement.

To help meet the space weather requirements of space launch, the 45 WS coordinates very closely with the operational space weather providers. Unfortunately, space environment characterization is years, and many research projects away from being able to provide system-specific information needed to accurately assess risk (Jedlovec, 2014; Merceret et al., 2013).

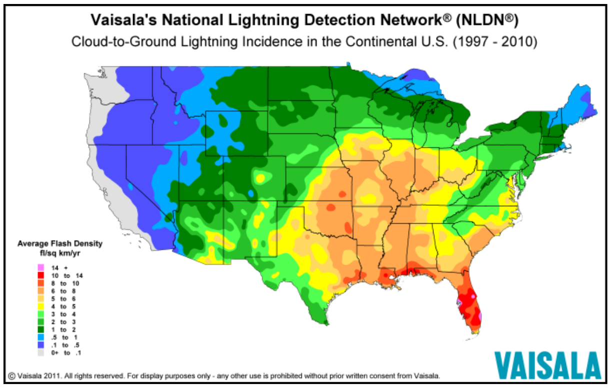

Figure-1. Average annual U.S. cloud-to-ground lightning flash density.

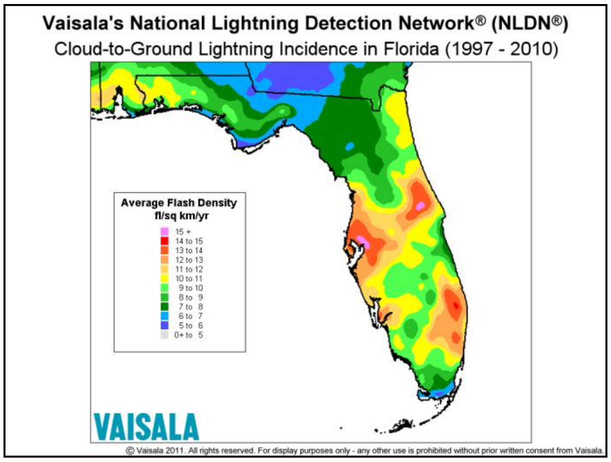

Figure-2. Average annual Florida cloud-to-ground lightning flash density.

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Due to the sensitivity of space launch and launch preparation to terrestrial weather, the frequency of thunderstorms and associated hazards, and the complexity of the local weather infrastructure, the 45 WS has many research requirements to improve weather support to America's space program. This paper will discuss those research requirements and opportunities. There are two topics that have the potential for significant improvement in several areas of operational importance to 45 WS: local numerical modeling and dual polarization radar. The space weather research requirements are best left to the space weather operators and space weather scientists and will not be discussed here. This paper is a major update to previous articles on the research needs (Roeder et al., 2006; Roeder and Madura, 2004; Boyd et al., 2003; Roeder et al., 2003; Wilfong et al., 2002; Roeder et al., 2002a; Harms et al., 2001; Roeder and Harms, 2000; Lucci et al, 1998; Roeder et al., 1996; Madura et al., 1991; Kolczynski, 1986; Boyd et al., 1985).

The 45 WS has very limited funding for weather support improvement initiatives. However, sometimes funding for deserving projects can be found. Sometimes collaborative projects that are consistent with projects with other funding can be negotiated. Finally, sometimes small projects are done at no financial cost. Although the 45 WS rarely can fund projects, there are other opportunities: free access to the numerous local weather sensors used by 45 WS, access to the decades of local meteorological expertise of the 45 WS personnel and other meteorologists on the local weather team, well defined research projects, a research coordinator to avoid duplication of effort and identify opportunities for synergy, and a well-established process for transitioning research into operations.

Anyone interested in funding or conducting research with the 45 WS is encouraged to contact the corresponding author.

2. 45 WS Research Requirements

The 45 WS has identified 14 topics in which research is required to improve weather support to CCAFS/KSC (Table-1). These topics are discussed below in priority order based on impact on operations, likely gain in performance, and cost. These discussions are necessarily brief. The full list of topics includes considerable more detail, many including several specific projects within each topic. Anyone interested in any of the following research topics should contact the corresponding author.

TABLE-1

Desired research topics for the 45 WS.

Priority	Topic
1	Lightning Cessation
2	Lightning Onset
3	Local Numerical Modeling for 45 WS
4	Convective Winds
5	Dual Polarization Radar Applications
6	Tools for Daily 24-Hr and Weekly Planning Forecasts
7	Elevated Point Peak Winds at the Launch Pads in Winter
8	Improved Lightning Launch Commit Criteria
9	Tropical Cyclone Impacts Tools
10	Lightning Detection, Warnings, Reports
11	Optimized Lightning Aloft Flash Algorithm
12	Rocket Amplification of Ambient Electric Fields
13	Data Visualization
14	Statistical Process Control Applications

2.1 Lightning Cessation

The 45 WS issues over 2,500 lightning advisories each year on average for CCAFS, KSC, and PAFB. A two tiered method is used, as summarized in Table-2 (Weems et al., 2001). These lightning advisories are issued for 10 lightning warning circles on CCAFS, KSC, and PAFB (Figure-3).

TABLE-2

The lightning advisory process used by 45 WS.

ADVISORY	ISSUED WHEN
Phase-1 Lightning Watch	Lightning is expected within the lightning warning circle(s) with a desired lead-time of 30 min
Phase-2 Lightning Warning	Lightning is imminent or occurring within the lightning warning circle(s)

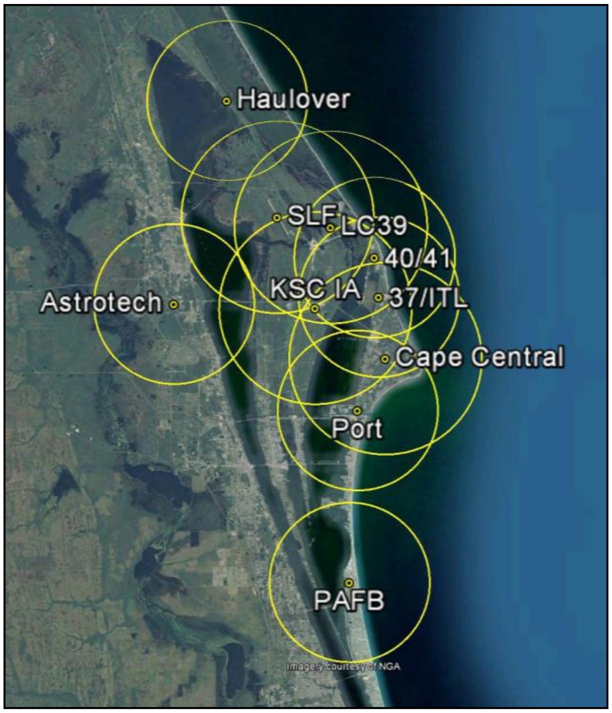


Figure-3. The 10 lightning watch/warning areas supported by the 45 WS. Each area is a circle with a 5 to 6 nmi radius, depending if one or several facilities are protected by that circle, respectively.

After-the-fact analysis shows that the 45 WS leaves its lightning watches and warnings in effect too long. Considerable savings to ground processing would result if a reliable, repeatable, object method for forecasting lightning cessation were available. Unfortunately, much less research has been dedicated to forecasting the end of lightning as compared to the start of lightning. This topic is the most important research area for the 45 WS for several reasons: the frequency of lightning in the 45 WS area, impact on space launch operations especially ground processing, relatively poor performance of forecasting lightning cessation, the lack of research on the topic, and opportunity for improvement.

Likely approaches to improved lightning cessation include statistical analysis of time since no lightning observed, radar techniques, field mill techniques, and integration of these methods. Some research has been dome on the statistical approach (Roeder, 2013; Stano et al., 2010; Stano et al., 2008a; Stano et al., 2008b; Roeder and Glover, 2005). Some research on radar and lightning cessation has also been done (Holmes, 2000; Hinson, 1997). When radar lightning onset thresholds are no longer met, presumably lightning cessation has begun, but the timing until last flash has been problematic. Some research using dual polarization radar has also been done (Preston, 2012; Preston and Fuelberg, 2012; Melvin and Fuelberg, 2010; Petersen et al., 2009; Carey et al., 2008). More recent dual polarization radar studies indicate that the absence of graupel at -10 °C may be useful in combination with “time since no lightning observed” (Fuelberg and Preston, 2012; Preston, 2012). Finally, some limited studies of surface electric fields in lightning cessation have been done (Beasley et al., 2008; Nicholson and Mulvehill, 1990). While this approach showed little promise, further research is needed.

2.2 Lightning Onset

The second most important topic requiring research is lightning onset. Considerable research has been devoted to forecasting when lightning will start, including that by the 45 WS, sponsored by the 45 WS, and others. One special need for lightning advisories is forecasting a first lightning flash of lightning aloft, as opposed to the probability of lightning, cloud-to-ground lightning, or flash density.

The primary tool for forecasting locally developing thunderstorms is traditional weather radar (Roeder and McNamara, 2011; Yang and King, 2010; Machina, 2009; Wolf, 2007; D’Arcangelo, 2000; Forbes and Hoffert, 1999; Gremillion and Harms, 1999; Gremillion and Orville, 1999; Roeder and Pinder, 1998; Forbes, 1994; Hondl and Eilts, 1994; Marshall and Radhakant, 1978). Another tool is local convergence detected by the network of weather towers in and around CCAFS/KSC (Roeder et al., 2002b; Roeder and Pinder, 1998; Watson et al., 1991; Holle et al., 1988).

The network of surface electric field mills on CCAFS/KSC can also be used to indicate if clouds overhead are electrifying. However, these field mills are not useful for precision lightning advisories (Hyland et al., 1999; Murphy et al., 2008a; Williams et al, 2008; Beasley et al., 2008; Montanyá et al., 2004; Rison and Chapman, 1988; Poehler, 1978).

Despite the previous research and considerable experience in issuing lightning advisories, there is still room for improvement. In particular, longer lead-times with the same or better performance are desired. A new application of dual-polarization radar is one likely source of this improvement, especially Z_{DR} columns (Thurmond, 2014; Woodward et al., 2012; Woodward, et al., 2011; Wiebke et al., 2009;

Petersen et al., 2009; Deierling, et al., 2008; Kasparis et al., 2002).

Another possible source to improve lightning warnings is the research using multi-spectral signals from the GOES satellite to predict the onset of deep convection and onset of lightning (Mecikalski et al., 2013; Harris et al., 2010; Harris, 2010). Some results indicate reliable prediction of lightning about 1.5 hours before onset is possible. This lead-time is significantly better than the minutes to 10-20 minutes typical of radar prediction of lightning and even longer than the desired 30 min desired lead-time for 45 WS lightning watches (Table-2). However, these techniques need to be verified in east central Florida in summer.

Another item of interest is the System for Convection Analysis and Nowcasting and AutoNowcaster (Mueller et al., 2003). These systems have the potential to improve thunderstorm forecasting, but needs to be tested in the subtle weakly driven environment of central Florida in summer.

The 45WS has also explored the utility of timelines of GPS-based precipitable water in predicting local thunderstorm for lightning warnings and for the entire day (Roeder et al., 2010; Kehrer et al., 2008; Mazany et al., 2002). While initially showing promise, a more recent result showed that GPS-based precipitable water adds little new independent skill beyond the daily lightning probability tool previously developed by the Applied Meteorology Unit (Huddleston, 2012). The lightning probability tool will be discussed in section 2.8.

An unusual topic on lightning onset deals with nocturnally forming lightning. Sometimes thunderstorms form in the CCAFS/KSC for no obvious reason, i.e. not previously occurring lightning that moved into the area. Though rare, these nocturnally forming thunderstorms often surprise the forecaster. A technique to predict these events would be useful. An initial study to establish a climatology of the nocturnally has been done and stratification by flow regimes suggest it may be associated with south-east flow regimes, perhaps due to low-level convergence lines off the Bahamas Islands (Kelly et al., 2010). Earlier preliminary research hinted it may occur under especially unstable atmospheres (Cantrell, 1999). More climatological work is needed, which could lead to a predictive tool. It would also be interesting to see if a local numerical model can predict these events.

2.3 Local Numerical Modeling for 45 WS

Local numerical modeling could provide improved forecasts support for several aspects of 45 WS weather support to space launch customers (Muggleberg, 2013). A local modeling has been tuned for optimum performance by the Applied Meteorology Unit (AMU) and is currently being evaluated by the AMU (Watson, 2014; Watson, 2013). The AMU provides technology transition and technique development to improve weather support to America’s space program (Jedlovec et al., 2014; Merceret et al., 2013; Madura et al., 2011; Bauman et al., 2004; Merceret et al, 2004; Ernst and Merceret, 1995). This model has an inner grid spacing of 1.33 km. This small inner grid spacing is needed to begin depicting the river breeze fronts from the Indian River and Banana River, which can be as important as the sea breeze front in causing local thunderstorms. Preliminary results indicate this local model is doing well in predicting local thunderstorms. Earlier modeling studies were also done (Case et al., 2004; Case et al., 2000; Watson, 2011; Bauman, 2010; Watson, 2007; Rogers et al., 2000; Nutter and Manobianco, 1999a; Nutter and Manobianco, 1999b).

Future improvements to the local model could include refining the inner grid spacing to as little as 300 m to fully resolve the river breeze fronts (Rao et al., 1999). In addition, detection of the water temperatures across the Indian River and Banana River in near real-time is needed to better forecast the river breeze fronts (LaCasse et al., 2008). Another way to enhance the local numerical model would be detection of soil moisture in the local area on a fine scale. Where the soil is wetter/drier, the soil and adjacent atmosphere will heat slower/faster, which leads to low-level contrasts in the planetary boundary layer. Although these soil moisture driven atmospheric boundaries are very weak, their intersection with other boundaries can still contribute to thunderstorm formation in the Florida summer, since the synoptic forcing is so weak then. Another area to explore is ensemble forecasting (Doran et al., 1998). Questions to address include how to best generate the ensembles (perturb initial observations, use various physical parameterizations, use previous forecast(s) valid the current analysis time, the best balance between number of ensemble members and run-time, the forecast performance benefit of ensembles vs. single best forecast, and how to interpret the ensembles.

2.4 Convective Winds

The 45 WS issues an average of about 175 convective wind warnings a year and is the second most frequent advisory product issued. These warnings are issued for winds ≥ 35 kt with a desired lead-time of 30 min and ≥ 50 kt with a desired lead-time of 60 min.

Four approaches to convective wind warnings have been researched by the 45 WS. The climatology of convective winds at CCAFS/KSC has been extensively studied using the local weather tower network (Ander et al., 2009; Dinon, 2009; Cummings et al., 2007; Loconto, 2006; Sanger, 1999). The speed distribution when downbursts occur has been especially useful. Downbursts ≥ 35 kt occur in 31.8% of downbursts, ≥ 50 kt occur in 5.8% of downbursts (Lupo, 2013). Therefore, if downbursts are expected, the lower warning should generally be issued to reduce missed warnings, even at the cost of false alarms, unless there is good evidence that peak winds will not exceed 35 kt. However, warnings for the second threshold should generally not be issued unless there is strong evidence that peak winds will be 50 kt or greater. The climatology also showed the role of both flow regimes and number and type low level boundary interactions in producing downbursts. Future research should calculate the frequency of downbursts occurring at any point on CCAFS/KSC, as opposed to the entire area of CCAFS/KSC as has been done in the past. The frequency and intensity of downbursts across CCAFS/KSC and if the differences are statistically significant could also be explored.

The weather towers were also used to determine the utility of the most distant in-land weather towers in 45 WS convective wind warnings (Koermer and Roeder, 2008). These towers were not as useful as the other towers, which became part of the justification in decommissioning those towers to save maintenance costs. Part of the reason was low availability of those towers due to difficult maintenance due to distance and swampy terrain. However, even when data from those towers are available, it tends to not be useful in convective wind warnings for CCAFS/KSC. When thunderstorms approach the area, they tend to not produce warning level winds until they enter CCAFS/KSC. This may be due to thunderstorm interaction with local low-level boundaries like the sea breeze front, Indian River and Banana River breeze fronts. This may not be surprising since earlier research on downbursts implied the importance of low-level boundary interactions in downburst production (Rinehart et al., 1995; Wolfson, 1990).

Considerable research has been performed on Rawindsonde Observation (RAOB) parameters to predict downbursts (McCue, 2010; Dickerson et al., 2000; Dickerson, 2000; Wheeler, 1997; Wheeler and Roeder, 1996; McCann, 1994; Atkins and Wakimoto, 1991). These are considered outlook techniques, i.e. the morning outlook for winds from convection usually that afternoon. However, these indexes have had poor performance in the small area of CCAFS/KSC. However, an ensemble Categorical And Regression Tree (CART) showed promise (McCue, 2010). Future research should reverify that ensemble CART and explore how to implement it into operations. Other research could focus on using a RAOB to predict downbursts over a larger area.

Intermediate techniques bridge the gap between RAOB morning outlook techniques with hours of lead-time and radar nowcast/warning techniques with minutes of lead-time. The intermediate techniques use GOES sounding profiles to simulate updated RAOBs (Pryor and Ellrod, 2004; Ellrod et al., 2000; Ellrod, 1989). Proposed improvements include isoplething and coloring GOES sounder downburst products over an area at a single time, timelines of GOES downburst products at a single point, and smoothing techniques to interpolate the GOES products to fill-in gaps caused by clouds.

Nowcast or warning techniques provides minutes to tens of minutes before the convective winds. These techniques are usually radar-based. Some research has been done on this topic using traditional weather radar (Rennie, 2010; Sullivan, 1999; Wheeler, 1998; Mackey, 1998). A radar-based automated warning tool has been developed, adapted from Rennie (2010). This tool indicated which cells are capable of producing convective winds ≥ 35 kt based on VIL and VIL density. More research is required, especially in applying ensemble Categorization And Regression Tree Radar techniques (Rennie, 2010). Additionally, dual-polarization radar has considerable potential to improve convective wind warnings (Scholten, 2013; Scott et al., 2012; Harris, 2011; Atlas et al., 2004). However, more development is required before these techniques can be used operationally. Ultimately, a dual-polarization Doppler radar combined with ambient environment information could completely solve the convective wind challenge. The ambient environment knowledge could come from nearby

RAOBs of local models. The Doppler radar could indicate mid-level convergence entraining the ambient air into the cell. The dryness of that air relative to the humidity of the cell at that altitude would indicate the amount of evaporational cooling starting the downdraft. The dual polarization radar could indicate the type, depth, and number density of various hydrometeors needed to sustain the downdraft and how much of the downdraft survives to reach the surface to form the downburst outflow.

Much of the 45WS research on convective winds was done under a NASA-New Hampshire Space grant. Most of the data are archived and well organized for use by other researchers, especially the weather tower, CCAFS RAOB, and WSR-88D/Melbourne radar. These data are at http://vortex.plymouth.edu/conv_winds.

2.5 Dual Polarization Radar Applications

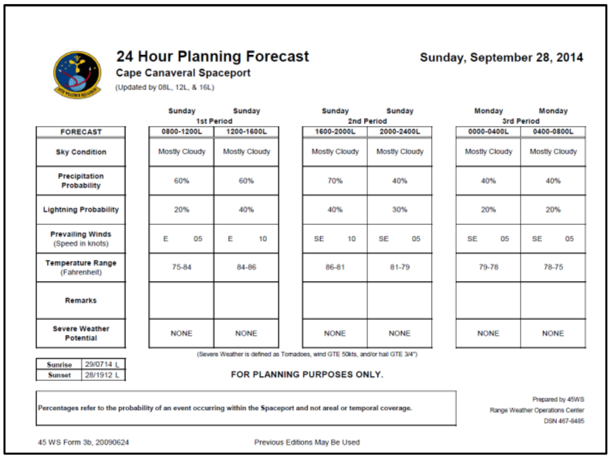
Dual polarization radar has been mentioned as a possible solution in several previous topics, especially lightning cessation, lightning onset, convective winds, and lightning launch commit criteria. The 45 WS has recently acquired a C-band dual-polarization Doppler radar to help improve operations (Roeder et al., 2009). Since dual polarization could be so important to improving so many areas of 45 WS operations, it is listed as a separate research topic to emphasize its importance.

Some research has been done to improve the use of this radar. The scan strategy was customized to the 45 WS mission (Roeder and Short, 2009) including outstanding detection of low-level boundaries for thunderstorm prediction, excellent vertical resolution of the atmospheric electrification layer for lightning prediction and evaluation of Lightning Launch Commit Criteria, good detection of anvil clouds, some fill-in of the cone of silence, additional angles for good vertical continuity, all with a fast volume scan of 2.6 min. The annual mean and variability of various temperature levels is vital for specifying the atmospheric electrification layer. While this gives excellent coverage for anytime in the year, it can waste some beam angles on any individual day. Therefore, a temperature adaptive scan strategy was developed to meet the above operational goals while optimizing the beam angles (Carey et al., 2009a).

Some preliminary research has been done on using dual polarization radar to infer electric fields aloft under some conditions by detecting orientation of ice crystals (Carey et al., 2009b). The hope is related techniques will eventually improve prediction of lightning onset, cessation, and even evaluation of Lightning Launch Commit Criteria.

2.6 Tools for Daily '24-Hour' and 'Weekly' Planning Forecasts

The 45 WS issues a daily 24-hour and Weekly planning forecast. An example of each is shown in Figure-4 and Figure-5, respectively. The most important parameters in these planning forecasts are the probability of lightning and its timing during the summer, the probability of rain and its timing, the likelihood of severe weather during the summer, and the expected wind speed, direction, and timing of wind shifts. Considerable research has been done to develop tools to forecast these parameters, but more work is still required.



24 Hour Planning Forecast **Sunday, September 28, 2014**
Cape Canaveral Spaceport
(Updated by 08L, 12L, & 16L)

	Sunday	Sunday	Sunday	Sunday	Monday	Monday
	1st Period		2nd Period		3rd Period	
FORECAST	0800-1200L	1200-1600L	1600-2000L	2000-2400L	0000-0400L	0400-0800L
Sky Condition	Mostly Cloudy	Mostly Cloudy	Mostly Cloudy	Mostly Cloudy	Mostly Cloudy	Mostly Cloudy
Precipitation Probability	60%	60%	70%	40%	40%	40%
Lightning Probability	20%	40%	40%	30%	20%	20%
Prevailing Winds (Speed in knots)	E 05	E 10	SE 10	SE 05	SE 05	SE 05
Temperature Range (Fahrenheit)	75-84	84-86	86-81	81-79	79-78	78-75
Remarks						
Severe Weather Potential	NONE	NONE	NONE	NONE	NONE	NONE

(Severe Weather is defined as Tornadoes, wind GTE 50kts, and/or hail GTE 3/4")

Sunrise	29/0714 L
Sunset	28/1912 L

FOR PLANNING PURPOSES ONLY.

Percentages refer to the probability of an event occurring within the Spaceport and not areal or temporal coverage.

Prepared by 45WS
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DSN 467-8485

45 WS Form 3b, 20090624
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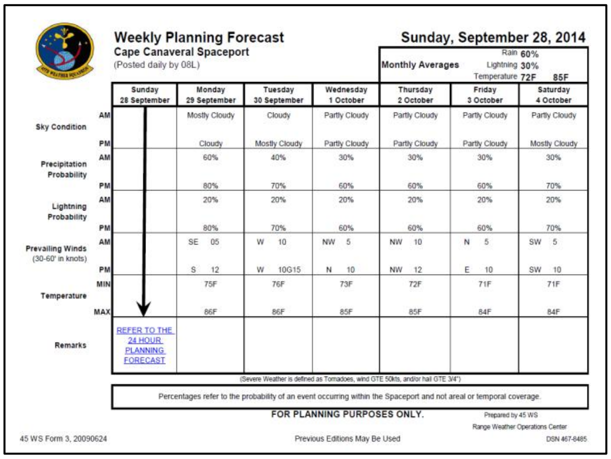
Figure-4. Example daily 24-Hour Planning Forecast issued by the 45 WS.



Weekly Planning Forecast **Sunday, September 28, 2014**
Cape Canaveral Spaceport
(Posted daily by 08L)

Monthly Averages
Rain 60%
Lightning 30%
Temperature 72F 85F

		Sunday 28 September	Monday 29 September	Tuesday 30 September	Wednesday 1 October	Thursday 2 October	Friday 3 October	Saturday 4 October
Sky Condition	AM		Mostly Cloudy	Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy
	PM		Cloudy	Mostly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Mostly Cloudy
Precipitation Probability	AM		60%	40%	30%	30%	30%	30%
	PM		80%	70%	60%	60%	60%	70%
Lightning Probability	AM		20%	20%	20%	20%	20%	20%
	PM		80%	70%	60%	60%	60%	70%
Prevailing Winds (30-60' in knots)	AM		SE 05	W 10	NW 5	NW 10	N 5	SW 5
	PM		S 12	W 10G15	N 10	NW 12	E 10	SW 10
Temperature	MIN		75F	76F	73F	72F	71F	71F
	MAX		86F	86F	85F	85F	84F	84F
Remarks		REFER TO THE 24 HOUR PLANNING FORECAST						

(Severe Weather is defined as Tornadoes, wind GTE 50kts, and/or hail GTE 3/4")

Percentages refer to the probability of an event occurring within the Spaceport and not areal or temporal coverage.

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Range Weather Operations Center
DSN 467-8485

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Figure-5. Example of daily Weekly Planning Forecast issued by the 45 WS.

A new lightning probability tool was developed by the AMU (Bauman and Crawford, 2012; Crawford, 2010; Lambert and Roeder, 2008; Lambert et al., 2006). This tool provided 56% better skill compared to the original tool. The AMU project was an extension of earlier work to improve the original 45 WS lightning probability tool (Everitt, J. A., 1999; Howell, C. L., 1998; Wohlwend, C. S., 1998). The AMU project also incorporated the work by Florida State University that explored prediction of thunderstorms driven by sea breeze fronts (Cantrell, 1999; Rao et al., 1999; Kelly et al., 1998; Cetola, 1997) funded under the COMET/AFWA FSU/45 WS Outreach Program. This project led to the concept and application of lightning flow regimes for central Florida (Stroup, 2003; Lericos et al., 2002).

These projects were inspired by recognizing the shortfalls of the original 45 WS lightning probability tool, the Neumann-Pfeffer Index (Neumann and Nicholson, 1972; Neumann, 1971; Neumann, 1968). Other related work at FSU was done by Shafer and Fuelberg, 2006a; Shafer and Fuleberg, 2006b). There are two likely opportunities to further improve the AMU lightning probability tool. Stratifying the predictive equations by lightning sub-season, rather than my arbitrary months, should be developed. The lightning sub-seasons are: out of season, preseason, ramp-up, main season, ramp-down, and post-season. This was attempted previously (Crawford, 2012), but there were difficulties in objectively identifying the sub-seasons. The other opportunity is considering the mean wind speed in the 1000-700 mb lightning flow regimes. Wind speed had been previously found to not be a statistically significant predictor (Crawford, 2010), but that speed was not stratified by flow regime.

In addition to lightning probability, another important factor is the timing of the lightning, especially the first lightning of the day. Some research on lightning timing has been done, but has not been very successful (Huddleston, 2013; Renwick et al., 2000; Renwick, 2000). More research is needed on this topic research.

The summer severe weather tool was recently upgraded (Bauman and Roeder, 2014a; Bauman and Roeder, 2014b). Further improvements might be possible, such as by applying logistic regression to calculate the probabilities directly, rather than arbitrary risk categories.

The AMU also developed a tool to forecast the mean and peak surface wind during the winter (Barrett, 2010; Barrett et al, 2008). This tool made an unusual application of the error bars from linear regression to predict the probability of exceeding the wind speed advisory and warning thresholds.

The local numerical model being developed by the AMU may be especially useful in improving these planning forecasts and verifications on the performance of that model and suggestions to improve the model are highly encouraged.

A recent project with Florida Institute of Technology is upgrading the 45 WS minimum temperature tool (Brownlee, 2014) and will provide significant improvement.

Another desired research project is improving the flowchart for predicting a nocturnal land-breeze (Case et al., 2007; Case, 2002), which is important in predicting low temperatures.

2.7 Elevated Point Peak Winds at the Launch Pads in Winter

Forecasting the elevated point peak winds at the launch pads in winter is one of the greatest forecast challenges of the 45 WS. The Launch Weather Officers must ensure a 1-second peak wind speed threshold will not be exceeded for hours during a launch window while the protective service towers are rolled back. These peak speeds are at a specific level that is usually a few hundred feet in altitude and launch pad location that varies by space launch vehicle. Since 1-second peak speeds are turbulent motion, it is impossible to explicitly predict its value at any instant. However, the probability of exceeding the threshold during a period can be predicted. This is primarily a problem during winter. While peak speeds are also difficult to forecast during summer, the winds then are usually so weak that they do not approach the operational thresholds.

Some tools have been developed for this purpose. Three early studies used conditional climatology (Cloys et al., 2000, Coleman, 2000) and neural networks (Cloys et al., 2000; Storch, 1999) to predict the peak winds. Unfortunately, the performance was insufficient, but did confirm the difficulty of the challenge--beating even simple persistence was difficult. Later work with the AMU applied peak speed distributions from the mean speed for the operational heights at the various launch pads (Lambert and Roeder, 2008; Lambert, 2002). In essence, since the 45 WS can predict the mean speed more accurately than the peak speed, the mean speed prediction is used to leverage a peak speed forecast through a conditional climatology of past mean-to-peak speed observations by level and location for the primary launch vehicles. This approach performs acceptably, but much more research is needed.

One possible approach to improve prediction of elevated peak winds at CCAFS/KSC is to use the recent time series of 1-hour mean speeds and associated gut factors over several hours and extend the pattern several hours into the future. The tool would be updated every hour as new data becomes available. A Kalman Filter might be used to regress the peak speeds towards the climatological gust factor, piggybacking on the research from the previous tool. Other approaches could use Fourier or Wavelet decomposition, or cubic splines. The expected pattern of mean winds in the near future could come from a local numerical model, the past 24-hour diurnal curve, or the climatological diurnal curve. Another approach could investigate how well the current tool works when the mean speed forecast comes from the local numerical model. Finally, a specialized planetary boundary layer numerical model may be needed.

2.8 Improved Lightning Launch Commit Criteria

The Lightning Launch Commit Criteria (LLCC) are 11 weather rules to avoid natural and rocket triggered lightning to in-flight rockets (Merceret, 2010; Willett, 2010; McNamara et al., 2009; Barrett et al., 2008; Dye et al., 2007; Merceret et al., 2008; Krider, 2006; Merceret et al., 2006a; Merceret et al., 2006b; Roeder and McNamara, 2006, Ward and Merceret, 2004a; Ward and Merceret, 2004b; Merceret and Christian, 2000; Marshall et al., 1999a; Marshall et al., 1999b; Roeder et al., 1999a; Roeder et al., 1999b; Roeder et al, 1999c; Krider et al., 1999; Holland, 1988; Krider et al., 1974). This is a highly specialized topic and the Lightning Advisory Panel, a group of experts in atmospheric electricity, perform research to recommend improvements to the LLCC. While research on the LLCC themselves would be difficult for a M.S. thesis or even Ph.D. dissertation, there are some associated topics that would be appropriate for graduate students.

A climatology LLCC is the most important of the topics appropriate for graduate students. Knowing the frequency of violation of each of the 11 rules and if any rule is violated diurnally and monthly would help in designing Concept of Operations and mission planning. In addition, knowing the overall frequency of violation would help guide research on improving the LLCC themselves more efficiently. Some work has been done on LLCC climatology, but none of it has satisfied the requirement (Strong, 2012; Muller, 2010, Goetz, 2000). For example, the 45 WS analysis of LLCC violations for space launches (2005-2012) is useful but is anecdotal, having only been done during launch windows and so was not done at all times during an extended period (McNamara, 2013). Additional climatologies on the frequency of lightning strikes versus distance outside of cloud edges for cellular thunderstorms and anvil clouds would be useful as well as how far lighting can travel down attached anvil. Some work has been done on this, but larger sample sizes would be useful (Tamurian et al., 2012; Nelsen, 2002; Vollmer, 2002). Also needed is how often the first lightning aloft occurs in anvil without having first occurred in the parent thunderstorm. Especially useful would be the frequency distribution of lightning in detached anvil vs. time since separation from the parent thunderstorm.

For long-term improvement in the LLCC, a study of dual polarization radar signatures versus LLCC violations would be extremely useful. There is some evidence that dual polarization radar can infer electric fields via ice crystal orientation under some conditions (Carey et al., 2009b). However, it is not known if it can infer electric fields that can cause rocket triggered lightning. Likewise, the presence of certain hydrometeor species at certain temperature levels may correspondence to electric fields strong enough to cause rocket triggered lightning as suggested by the research on lightning cessation and lightning onset.

2.9 Probability of Tropical Cyclone Impacts Tools

East central Florida is often threatened by tropical cyclones. Even though many of these tropical cyclones pass south of the area or recurve while east of the area, the 45 WS must confidently advise the launch customers if the approaching cyclones will not affect the area (Winters et al., 2006). The Wind Speed Probability Product from the National Hurricane Center has proven to be very useful. The performance of this product has been extensively studied, including some sponsored by 45 WS for land-falling tropical cyclones (Collins, 2013; Botambekov, 2011; DeMaria et al., 2013; Sampson, 2012; Splitt et al., 2010; Shafer, 2009; Shafer, 2008). Interpreting the Wind Speed Probability Product can be difficult since the operationally significant probabilities decrease at longer forecast intervals. A tool to help interpret this product for non-meteorological non-statistical decision makers was developed by the 45 WS (Splitt et al., 2014; Roeder and Szpak, 2011). The most recent version on the NHC product adapts the spread of the wind fields based on the forecast confidence as parameterized by the spread in the forecast models (DeMaria et al., 2013; DeMaria et al., 2009). One of the first attempts to use ensemble spread in that way was a research project suggested by 45 WS (Hauke, 2006), which later expanded in by Pearman (2011). Some local research has been done to refine the wind speed predictions for tropical cyclones at different altitudes at CCAFS/KSC that are important to space launch vehicle processing (Roeder and Huddleston, 2010; Merceret, 2009; Merceret, 2008).

2.10 Lightning Detection, Warnings, and Reports

2.10.1 Lightning Detection

The 45 WS uses the Four Dimensional Lightning Surveillance System (4DLSS) to detect both cloud-to-ground lightning and lightning aloft (Roeder and Saul, 2012; Flinn et al., 2010a; Flinn et al., 2010b; Roeder, 2010; Murphy, 2008b; Boyd et al., 2005; Boccippio, 2001). While 4DLSS performs well, it does have some room for improvement. It misses about 5% of all cloud-to-ground flashes due to strong local strokes (Mata et al., 2012; Sun, 2012; Ward, 2008). The near ground components of these strong strikes can generate signals that cause timing mismatches, resulting in no lightning solution. In addition, strikes to tall structures, such as launch pads, have a lower than normal detection efficiency or are sometimes misclassified as lightning aloft. These problems should be largely overcome by the 4DLSS replacement system that should become operational in 2015. Much work has been made to improve the location accuracy and detection efficiency of lightning detection networks. However, not as much work has been to improve the detection of cloud-to-ground peak current and peak current error. Peak current is important to 45 WS lightning applications since they are used to assess the risk of induced current damage to the electronics of payloads, space launch vehicles, and test equipment. The 45 WS has some proposals on how to improve the detection of cloud-to-ground lightning peak current and its errors, but research is required to develop and test those proposals. Since the 4DLSS is used to assess the risk of induced currents from nearby lightning, the rise times, dI/dt, of the currents from individual strokes are needed. The 4DLSS does not report rise time, but the replace system does. However, the range of those rise times is very small distance around the individual sensors. Measuring the range of the rise times and their accuracy would be useful, as would extending the range if needed. In addition, the space launch customers will require assistance in learning how to apply dI/dt in their procedures.

2.10.2. Lightning Warnings

The 45WS lightning warnings were briefly discussed in section 2.1. In the past, some research was done to address in 5 nmi is the optimum distance for point lightning warnings, providing the best balance between personnel safety, resource protection, and operational impact (McNamara, 2002; Scott, 2001; Parsons, 2000; Cox, 1999; Renner, 1998). The final conclusion of these studies was that 5 nmi is the optimum distance for lightning warnings, when the warnings are issued based on the edge of the lightning field, as done by 45 WS, rather than the middle of the thunderstorm (Roeder, 2008).

The 45 WS has also researched optimizing the number and location of their lightning warning circles (Ceschini, 2013; Roeder, 2013; Bowman, 2009; Roeder, 2008; Holle et al., 2003; McNamara, 2002). If there are too few warning circles, lightning warning circles, then some locations will have too many false alarms. If there are too many warning circles, then the warnings exceed the state of the art in lightning forecasting and increases the work load of the forecasters, distracting them from issuing/cancelling the best warnings. A new set of lightning warning circles were implemented in May 2014. These new circles reduced the number of lightning warning areas from 13 to 10 to streamline 45 WS operations and hopefully allow improved lightning advisories. This was done by assigning closely located facilities to same warning circle and increasing the size of the circle so that safety was preserved. Four of the ten lightning warning circles now have a radius of 6 nmi, to provide enough safety for all the facilities covered by the circle. The other lightning warning areas, for individual facilities, maintained the previous safety buffer of a 5 nmi radii. Another benefit of the new lightning warning circles was locating their centers with greater precision. Due to old display technology with a precision of only 0.01 degree of latitude/longitude, the centers of the circles could be mislocated by up to nearly 0.75 nmi. The new circles are now located to the nearest 0.001 degree latitude/longitude, providing a precision of less than 100 ft. Further research is needed on the new lightning warning circles. The 45 WS needs measurement of the increased warning times of the new warning circles as compared to the previous circles, i.e. increased needless false alarms. In addition, 45 WS had recommended consolidating launch pads 40 and 41 into one

6 nmi circle, but the launch customers did not accept that proposal out of concern for lost productivity from increased needless warning time. If the amount of warning time could be determined, that might be evidence to convince the launch customers to accept the consolidated lightning warning circles.

2.10.3. Lightning Reports

The 45 WS provides daily reports of cloud-to-ground lightning strikes to their space launch customers whenever strikes occur within 5 nmi of key facilities. These reports include the date, time, distance to the strike, peak current, distance to the lightning location error ellipse and the probability that the strike is within a critical radius. The latter is another example of how research has improved 45 WS operations. These daily reports are used by the space launch customers to assess the risk of induced current damage from nearby lightning strokes in delicate electronics in payloads, space launch vehicles, test equipment, and other key facilities. The past 6 years has seen a revolution in the daily lightning reports, including six major enhancements: 1) detection of cloud-to-ground strokes vs. flashes, 2) location error ellipses tailored to each stroke rather than one best-case location accuracy for all strokes, 3) scaling error ellipses to the more meaningful error levels of 99% and 95%, depending on the customer, rather than the 50% ellipse provided by the 4DLSS processor, 4) on-demand reports available within minutes for use during count-downs and other high-impact operations as opposed to waiting for the morning of the next business day, 5) calculate the probability of any stroke, with any error ellipse, within any critical radius, of any facility, (Huddleston et al., 2012; Huddleston et al., 2010) and 6) accounting for the error in the peak current measurement. Future improvements would be inclusion of the improvements discussed under lightning detection: more accurate peak current, more accurate peak current error, and current rise-time.

2.11 Optimized Lightning Aloft Flash Algorithm

The Lightning Detection And Ranging (LDAR) system has been recording lightning aloft in the CCAFS/KSC area since the early 1990s. This archive is a tremendous resource for research on lightning aloft. This is especially important to the 45 WS since so much of their operations deal with lightning aloft, e.g. lightning warnings and Lightning Launch Commit Criteria. Unfortunately, the LDAR data are extremely large and difficult to use. Converting that data to flashes would greatly facilitate lightning research. Some simple algorithms exist for converting LDAR to flashes, but significant improvement is possible (Murphy, 2006). One example of possible improvement is making the algorithm adaptive to LDAR data density. Another improvement would be a filter for random radio noise. For older LDAR data, filter aircraft flying through clouds at temperatures ≤ 0 C. Once an optimized LDAR flash algorithm is created, a database of LDAR flashes could be created. That database would greatly facilitate lightning research dealing with lightning aloft.

2.12 Rocket Amplification of Ambient Electric Fields

The Lightning Launch Commit Criteria are the same for all rockets launched from the U.S. Presumably, the threat of rocket triggered should vary depending on the length of the conductive exhaust plume and the length and shape of the rocket itself. Unfortunately, it is not known how to adjust the LLCC for individual rockets while maintaining the same high degree of safety. If the LLCC could be adjusted, this would increase launch availability and reduce launch costs.

2.13 Data Visualization

The 45 WS uses some weather sensors that detect the same phenomena. This is especially true of winds and lightning. One lightning task has been explored (Darwin, 2000). It would be useful if automated tools existed that could integrate those sensors into one internally consistent data and display those data for easy visualization and easy use by the forecasters.

2.14 Statistical Process Control Applications

Statistical process control, at its simplest, is a set of rules to identify when nonrandom departures from a process have occurred. If non-random departures toward worse performance occur, then investigation for corrective action should be done. If nonrandom departures towards better performance occur, then investigation to institutionalize the improvement should be done. The authors do not know of any applications of statistical process control in meteorology.

There are two likely applications of statistical process control to 45 WS applications. The first is the traditional application of continuous monitoring of product quality. In this case, the products would be the forecasts and warnings issued by the 45 WS.

The second likely application is a nontraditional application: real-time monitoring weather sensors. The most important topic requiring research is lightning cessation.

3. Research Advantages

There are several advantages to doing research with the 45 WS. First, there is a dense network of diverse weather sensors available. Most of these data are archived and quickly available at no financial cost to appropriate research projects. These weather sensors are shown in Figure-6 and listed in Table-3.

Another advantage to doing research with the 45 WS is access to operational meteorologists with many decades of experience in the local weather patterns. These meteorologists provide expert insight in guiding the research and help keep the research focused on operational improvements.

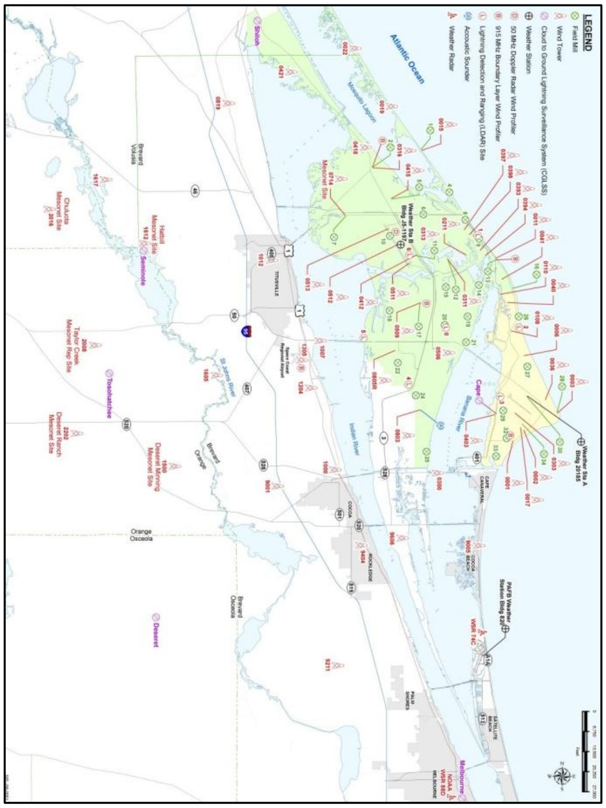

Figure-6. Map of local weather sensors used by the 45 WS. The far inland weather towers are no longer use.

TABLE-3

List of local weather sensors used by 45 WS. Most of these data are saved and are available for after the fact study.

SENSOR	NO.	COMMENTS
BOUNDARY LAYER		
Weather Towers	28	30 x 40 Km Area, 2 to 150 m, Wind, Temperature, Humidity
915 MHz DRWP/RASS	5	Wind (0.12-3 Km), 5 Min Virtual Temperature (0.12-2.5 Km), 15 Min
Surface Station	3	KSC, CCAFS, Patrick AFB
Rain Gauges	33	Most collocated at field mill sites (see LPLWS)
UPPER AIR		
Automated Meteo. Profiling System (AMPS) (Low-Res)	1	GPS-tracked RAOB (asynoptic times)
Automated Meteo. Profiling System (High-Resolution)	1	GPS-tracked Jimsphere (High precision wind balloon, countdowns only)
50 MHz DRWP	1	Winds (2.0-19.0 Km), 112 Gates (150 m spacing), 5 Min refresh rate. Currently being replaced.
LIGHTNING		
Lightning Detection And Ranging, 2nd gen. (LDAR-II)	9	Detects lightning aloft, Depicts 3-D structure
Cloud to Ground Lightning Surveillance System (CGLSS)	6	Improved Accuracy with Combined Technology (IMPACT) sensors
Launch Pad Lightning Warning System (LPLWS)	31	Surface electric field, Detects all lightning types (poor location accuracy and poor detection efficiency)
NLDN *	~105	Commercial data source
RADAR		
WSR-43/250	1	5 cm, 2.7 min Volume Scan, Customized Products
WSR-88D *	1	NWS/Melbourne

* Not a local weather sensor, but is included for its importance in operational research or for completeness.

Yet another advantage to doing research with 45 WS is consulting with meteorologists with extensive experience in operational research and transitioning research to operations. In particular, one of the jobs of one of the 45 WS civil servants is to facilitate research. This includes continual guidance on the research topics, suggested research approaches, facilitating access to the local weather data and local meteorological experts, leveraging past and present research data sets and lessons learned to complete new projects faster and better and avoid duplication of effort, alert the researcher to any interesting weather events germane to the research, and any other activity needed to facilitate the research. In addition, the Applied Meteorology Unit (AMU) can often assist in other 45 WS efforts. The AMU is an organization funded under a NASA contract to improve weather support to America's space program via technology transition and technique development (Jedlovec et al., 2014; Merceret et al., 2013; Madura et al., 2011; Bauman et al., 2004; Merceret et al, 2004; Ernst and Merceret, 1995). Some of the most significant contributions of the AMU to 45 WS operations include the new lightning probability tool that improved forecast skill by 56% over the original tool (references in section 2.8). The radar scan strategy, optimized to the 45 WS mission, improved vertical resolution in the atmospheric electrification layer by 36% for improved lightning warnings and evaluation of Lighting Launch Commit Criteria (section 2.9). The AMU developed the world's first tool to predict the trajectory of anvil clouds to help evaluate Lightning Launch Commit Criteria (Short et al., 2004). More recently, the AMU updated the summer severe weather tool for east central Florida (section 2.8). Currently, the AMU optimized a local numerical forecast model for the 45 WS and is verifying the model's performance (section 2.5). There are many more projects provided by the AMU. More information on the AMU is at their website, including reports on their past project is at their website (http://science.ksc.nasa.gov/amu).

Finally, researchers with 45 WS will have access to the documentation of 45 WS forecast procedures and instrumentation, training materials, and past research.

4. Summary

There are several opportunities to improve weather support to America's space program at CCAFS/KSC. The 45 WS has identified 14 research topics that would be most useful. Those topics were listed in Table-1, which is duplicated here for reader convenience. Two topics are of special interest since they have the potential to improve several aspects of 45 WS operations: local modeling and dual polarization radar.

There are several advantages to doing research for the 45 WS: availability of extensive detailed unique weather data, access to well-developed research plans, consultation with meteorologists with decades of experience with the CCAFS/KSC weather, and assistance from meteorologists with decades of experience in transitioning research-to-operations. Anyone interested in performing or facilitating this research is encouraged to contact the 45 WS (william.roeder@us.af.mil).

TABLE-1

Desired research topics for the 45 WS.

Priority	Topic
1	Lightning Cessation
2	Lightning Onset
3	Local Numerical Modeling for 45 WS
4	Convective Winds
5	Dual Polarization Radar Applications
6	Tools for Daily 24-Hr and Weekly Planning Forecasts
7	Elevated Point Peak Winds
8	Improved Lightning Launch Commit Criteria
9	Tools for Tropical Cyclone Impacts
10	Lightning Detection, Warnings, Reports
11	Optimized Lightning Aloft Flash Algorithm
12	Rocket Amplification of Electric Fields
13	Data Visualization
14	Applications of Statistical Process Control

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