# 688 Using Temperature Layered VIL As Automated Lightning Warning Guidance

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## 1. Introduction

The 45th Weather Squadron (45 WS) is the United States (U.S.) 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 AFB (PAFB). 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 and associated hazards. The climatological lightning flash density across the CONUS (Huffines and Orville, 1999) shows why Florida is known as the 'Thunderstorm Capital' of the U.S. (Figure-1). Within Florida, the lightning activity concentrates across Central Florida, also known as 'Lightning Alley' (Figure-2).

This paper will review the temperature layered Vertically Integrated Liquid (VIL) technique developed by the 45 WS to forecast the onset of lightning. Although this technique was developed many years ago, it has not been published previously. Since the temperature layered VIL technique was not published before, and since it is especially amenable to automated lightning forecast guidance, this paper will emphasize this technique. The 45 WS also has other techniques to forecast lightning, but those were published previously and so will only be reviewed briefly. The 45 WS also has some techniques to forecast lightning cessation, but that topic exceeds the scope of this paper and those techniques will not be discussed.

## 2. 45 WS Lightning Watches/Warnings

The 45 WS provides lightning watches and warnings for 14 locations at CCAFS/KSC/PAFB and other sites (Figure-3) (Weems et al., 2001). Each lightning watch/warning area is a circle of 5 nmi radius that serves as a safety buffer for the location. A two-tiered watch/warning process is used. If a thunderstorm is approaching or developing in the local area, a Phase-1 Lightning Watch is issued for the appropriate circle(s). If lightning is imminent or occurring, a Phase-2 Lightning Warning is issued for the appropriate circle(s). The two-tiered watch/warning process is summarized in Table-1.

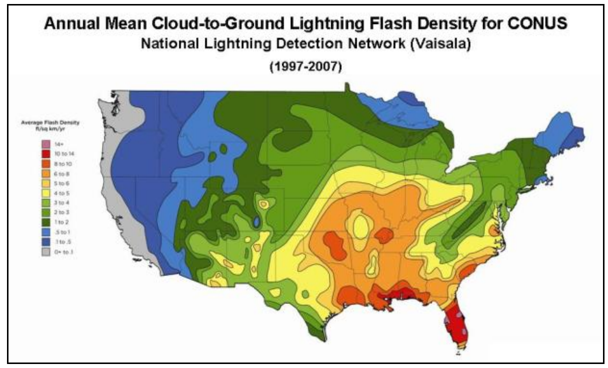


**Figure-1.** Average lightning flash density across the CONUS (1997-2007). Florida has the largest flash density. Data are from the National Lightning Detection Network. Graphic from Vaisala, Inc.

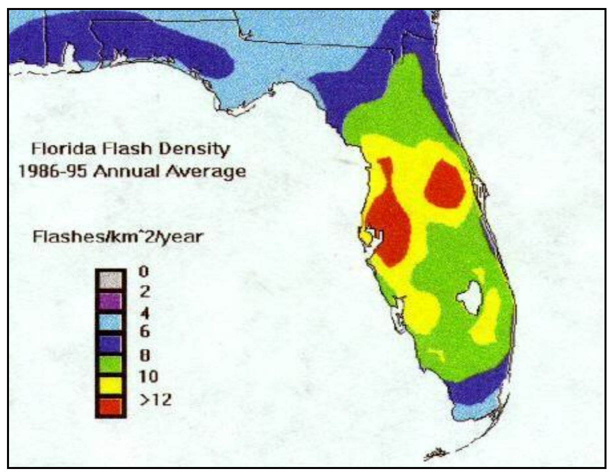


**Figure-2.** Average lightning flash density across Florida (1986-1995). The lightning activity concentrates across Central Florida. Data are from the National Lightning Detection Network. The Graphic is from the Melbourne Forecast Office of the National Weather Service.

Lightning watches/warnings are the most frequently issued products by 45 WS averaging 2,392 per year from 2002 through 2009. The small distances between many of the lightning watch/warning circles can be challenging. Under appropriate weather conditions, the 45 WS will issue or cancel a lightning watch/warning for one circle to allow a few minutes of work in an adjacent circle as close as only 2 nmi.

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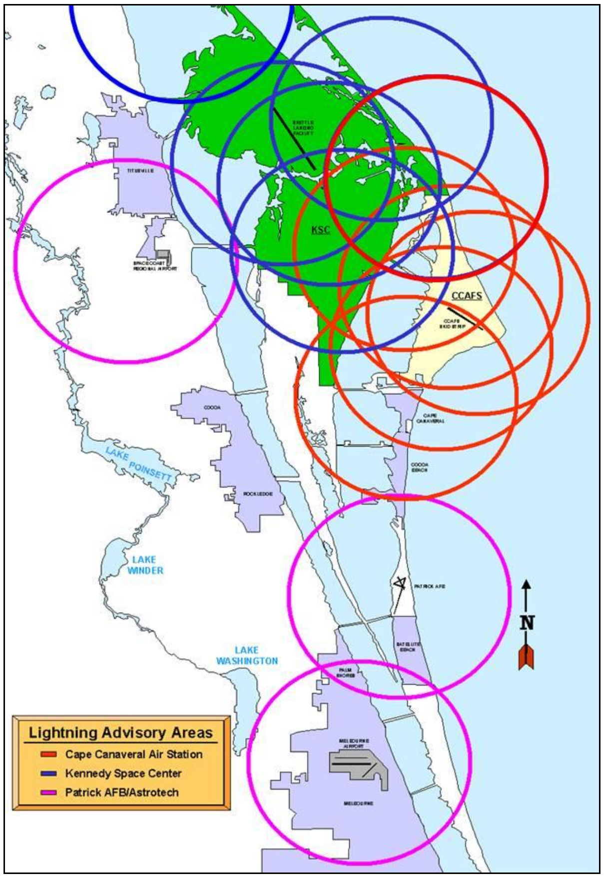


**Figure-3.** The 14 lightning watch/warning areas supported by 45 WS. Each area is a circle with a 5 nmi radius.

**TABLE-1**
The lightning advisory process used by 45 WS.

| ADVISORY | ISSUED WHEN |
|---|---|
| Phase-1 Lightning Watch | Lightning is predicted, within 5 nmi of the location(s), with a desired lead-time of 30 min |
| Phase-2 Lightning Warning | Lightning is imminent or occurring, within 5 nmi of the location(s) |

## 3. Lightning Forecasting At 45 WS

Forecasting the onset of lightning is obviously needed for the lightning watches/warnings discussed in section-2. The lightning forecasting tools and techniques used by 45 WS fall into four main categories: 1) climatology and current weather pattern, 2) continuity for preexisting thunderstorms approaching the area, 3) techniques for locally developing thunderstorms, and 4) miscellaneous other techniques.

### *3.1 Climatology and Current Weather Pattern*

As with most forecasting techniques, climatology and current weather patterns are the first step in lightning forecasting at 45 WS. The lightning probability tool is one of the main 45 WS techniques in this category. It considers two to three stability indexes, lightning flow regimes in peninsular Florida, mid-level moisture, 1-day persistence, and climatological daily lightning frequency, all optimized for each month of the lightning season at CCAFS/KSC (May-Sep). This tool was developed by the Applied Meteorology Unit (Madura et al., 2011; Bauman et al., 2004).

### *3.2 Continuity*

For preexisting thunderstorms that are approaching the area, lightning forecasting is relatively easy. The 45 WS uses several lightning detection systems, along with radar and satellite imagery, to predict when the lightning will be within the 30 min desired lead-time and within the lightning warning circles to decide when to issue a Phase-1 Lightning Watch or Phase-2 Lightning Warning, respectively. Of course, one must anticipate changes in motion, lightning rate, and areal extent of the lightning of approaching thunderstorms, such as from interaction with the plethora of low-level boundaries in central Florida during the summer. These low-level boundaries include the sea breeze fronts from the Atlantic Ocean and Gulf of Mexico, the local river breeze fronts from the Indian River and Banana River, convective outflows, horizontal convective rolls, frictional convergence lines, and many others.

One lightning detection system used by 45 WS is the Four Dimensional Lightning Surveillance System (4DLSS) (Murphy et al., 2008a). The 4DLSS detects all types of lightning including lightning aloft. The intra-cloud component of 4DLSS is often referred to by its previous name, the Lightning Detection And Ranging (LDAR), now LDAR-II (Boccippio et al., 2001). A map of the nine lightning aloft sensors in 4DLSS is at Figure-4. The cloud to ground lightning component of 4DLSS is often referred to by its previous name, the Cloud-to-Ground Lightning Surveillance System (CGLSS), now CGLSS-2 (Boyd et al., 2005). A map of the six cloud-to-ground lightning sensors in 4DLSS is at Figure-5. The second lightning detection system used by 45 WS is the Launch Pad Lightning Warning System (LPLWS) (Eastern Range Instrumentation Handbook, 2009), a network of 31 surface electric field mills that has a limited total lightning location capability. A map of the field mills in LPLWS as at Figure-6. The third lightning detection system used by 45 WS is a direct satellite link to the National Lightning Detection Network (NLDN) (Murphy et al., 2009; Orville et al., 2002). An illustration of the cloud-to-ground lightning detection process in NLDN is at Figure-7.

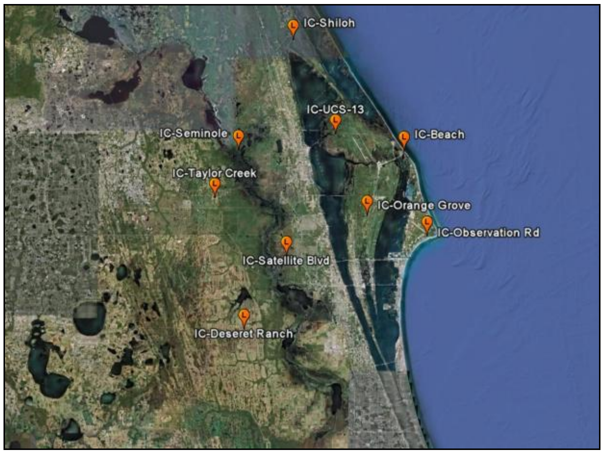


**Figure 4.** Map of the nine lightning aloft sensors in the Four Dimensional Lightning Surveillance System.

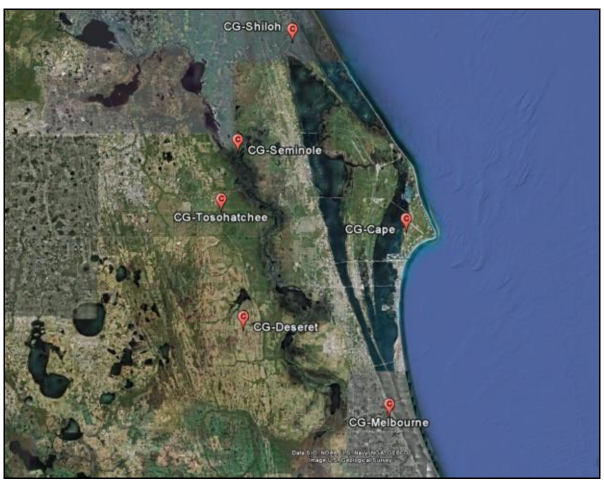


**Figure 5.** Map of the six cloud-to-ground lightning sensors in the Four Dimensional Lightning Surveillance System.

### *3.3 Locally Developing Thunderstorms*

Forecasting lightning from locally developing thunderstorms is more difficult than for preexisting thunderstorms approaching the area. The techniques to forecast lightning in locally developing thunderstorms are based primarily on radar. Many techniques for forecasting lightning with radar have been known for many years


**Figure 6.** Map of the 31 surface electric field mills in the Launch Pad Lightning Warning System.

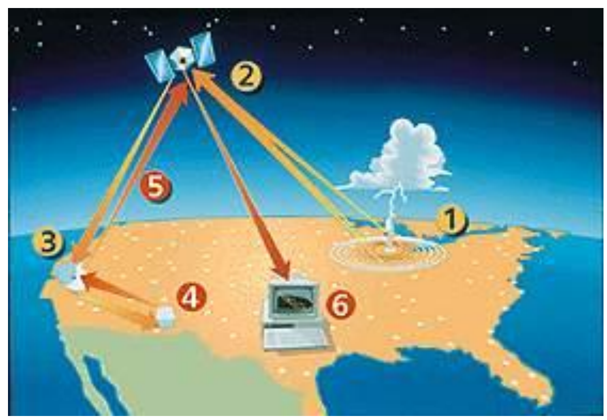


**Figure 7.** Illustration of the cloud-to-ground lightning detection process in the National Lightning Detection Network.

(Yang and King, 2010; Wolf, 2007; Gremillion and Orville,1999; Hondl and Eilts, 1994; Buechler and Goodman, 1990; Dye et al., 1989; Marshall and Radhakant, 1974). The 45 WS developed their own locally tuned radar techniques for forecasting lightning (Roeder and Pinder, 1998), which are listed in Table-2. The performance of 45 WS technique to predict cloud-to-ground lightning from a cellular thunderstorm technique is in Table-3 and compared to the Gremillion technique (≥ 40 dBZ at ≤ -10°C). Anvil cloud lightning techniques were developed since anvil clouds can produce cloud-to-ground lightning a very long distance from the parent thunderstorms, easily tens of miles, and in extreme cases well over 100 miles. Debris clouds form either by detaching from the parent thunderstorm, but are not anvil clouds, or are the remnant from a thunderstorm that stopped producing lightning of any type. Techniques to predict lightning from debris clouds were developed since they can produce cloud-to-ground lightning a very long time after what may have been thought to be the last flash, easily many tens of minutes, and in extreme cases over an hour.

**TABLE-2**

The original 45 WS radar techniques to forecast lightning (Roeder and Pinder, 1998). Since then, the 45 WS abandoned forecasting between lightning aloft and cloud-to-ground lightning. Later, automated guidance using temperature layered VIL was developed to supplement these rules (section-4).

| PHENOMENA | RULE |
|---|---|
| Cellular Thunderstorm Initial Lightning Aloft | ≥ 37-44 dBZ, above -10°C, by ≥ 3,000 Ft, with width ≥1 nmi*, for 10-20 min |
| Cellular Thunderstorm Initial Cloud-To-Cloud (CG) Lightning | ≥ 45-48 dBZ, above -10°C, by ≥ 3,000 Ft, with width ≥ 1 mile*, for 10-15 min |
| Anvil Lightning Aloft | ≥ 23 dBZ, ≥ 4,000 Ft depth, attached to parent Cb |
| Anvil CG Lightning | ≥ 34 dBZ, ≥ 4,000 Ft depth, attached to parent Cb |
| Debris Cloud Lightning Aloft | Tops ≥ 30,000 Ft, large volumes of ≥ 23-44 dBZ, above -10°C (smaller dBZ needs greater depth, e.g. 23 dBZ ≥ 10,000 Ft) |
| Debris Cloud CG Lightning | Tops ≥ 30,000 Ft, volumes of ≥ 45-48 dBZ exist |
| Lightning Cessation | When above criteria no longer satisfied, lightning is ending, but time until last lightning flash is highly variable |

**TABLE-3**

Performance of the 45 WS technique for first cloud-to-ground lightning from a cellular thunderstorm compared to the Gremillion method.

| | TECHNIQUE | |
|---|---|---|
| **METRIC** | **45 WS** | **GREMIILION** |
| Probability Of Detection (POD) | 0.72 | 1.00 |
| False Alarm Rate (FAR) | 0.18 | 0.29 |
| True Skill Statistic (TSS) | 0.44 | 0.31 |
| Mean Lead-time | 15 min | 7.5 min |
| Operational Utility Score (OUS)* | 0.48 | 0.56 |

** The Operational Utility Score was developed by 45 WS to evaluate lightning initiation techniques. An OUS of 0 means no utility, and 1 means perfect utility. Since lightning initiation is critical to personnel safety at CCAFS/KSC, this metric gives the largest weight to POD. Lead-time is also vitally important, but was not included in the OUS. The OUS is calculated as follows:*

*[3(POD) +2(KSS) -1(FAR)] / (3 + 2 + 1).*

Since the lightning prediction techniques were first developed in the late 1980s, the 45 WS abandoned differentiating between forecasting lightning aloft and cloud-to-ground lightning. Although it has been done with some success, the average time between the first lightning aloft and the first cloud-to-ground lightning is only about 4-5 min (Holle et al., 2003; Forbes and Hoffert, 1999; Forbes, 1994), so it is too risky for personnel safety and not useful enough to operations to try to discriminate in forecasting between the two types of lightning. Indeed, one of the applications of LDAR-II is to immediately issue a warning if lightning aloft is detected over a watch/warning circle to achieve a few minutes of lead-time before the first cloud-to-ground flash, even if it counts as zero lead-time or even a slightly after-the-fact warning. However, 45 WS uses LDAR-II for last minute lightning warnings only as a last resort, strongly preferring to forecast the onset of lightning aloft before it occurs to better meet the customers' desired lead-time of 30 min. Later, the 45 WS developed automated guidance for the first lightning aloft from cellular thunderstorms using temperature layered VIL, which is discussed in section-4.

*3.4  Miscellaneous Techniques*

The 45 WS uses other miscellaneous techniques to forecast lightning. The low-level convergence within the network of 44 weather towers in and around CCAFS/KSC is used to forecast the onset of a thunderstorm under some conditions (Watson et al., 1991; Holle et al., 1988). The isopleths of the convergence can indicate where a thunderstorm may develop well before the initial electrification begins and even before the convective cloud has formed.

The network of 31 surface electric field mills at CCAFS/KSC are used primarily to evaluate the lightning launch commit criteria to avoid triggered lightning strikes to in-flight space launch vehicles (McNamara et al., 2010). However, the field mills can also indicate if electrification is occurring in developing cumulonimbus clouds inside the field mill network. Likewise, the field mills can indicate if anvil or debris clouds are still electrified and may still be a lightning threat. Unfortunately, experience has shown that the field mills by themselves are not useful for precise timing of lightning watches/warnings at CCAFS/KSC. There is no threshold of electric field, rate of change of the electric field over time, or horizontal pattern of electric field that correlates well to lightning onset (Hyland et al., 2009; Williams et al., 2008; Beasley et al., 2008). Studies at other locations have also indicated that field mills are not very useful in lightning warnings (Murphy et al., 2008b; Montanyá et al., 2004; Nicholson and Mulvehill, 1990; Rison and Chapman, 1988).

## 4. Automated Lightning Warning Guidance Using Temperature Layered VIL

The reflectivity, temperature, and depth criteria in the lightning aloft in cellular thunderstorm technique (section-3.3) suggested a temperature layered VIL technique might be used to develop automated guidance for lightning warnings to one of the authors (Roeder). With this technique in mind, the VIL above the freezing level should correlate well to the onset of lightning and could be easily implemented as a WARN product in the Interactive Radar Information System (IRIS) (Vaisala, 2009), the radar display and analysis software used by 45 WS. Although a VIL between 0°C and -20°C should work best, the WARN product only supported VIL above a single level. Since relatively little VIL exists above -20°C, the VIL above 0°C serves well enough for operational lightning warnings. The WARN product was easier to implement with a VIL layered by height, rather than the physically more meaningful temperature. Fortunately, most of the lightning at CCAFS/KSC occurs during the lightning season when the freezing level height is fairly constant, so a climatological height of 0°C was proposed as a reasonable approximation for the actual freezing level. The average 0°C height at CCAFS/KSC during the summer is 13,100 Ft (Range Reference Atmosphere, 2006), which was used in this lightning warning product. Another 45 WS meteorologist, Mr. Clark Pinder (now deceased) subjectively tuned the temperature layered VIL threshold to optimize performance in lightning forecasting (Pinder, 1998). Those thresholds are listed in Table-4.

The temperature layered VIL technique was implemented as an automated graphical warning product. Every volume scan, the temperature layered VIL is available as a graphic product with color coded values. Areas that meet the threshold for lightning initiation are highlighted with a black hatched overlay and labeled with text labeled ‘LTNG’. In actual practice, the ‘LTNG’ hatching based on the Layered VIL threshold is overlaid on a product commonly displayed on the 45 WS preferred 4-panel display, the 10 KFt Constant Altitude Plan Position Indicator display (Table-8). This is done to maximize the utility of limited radar display area. If a ‘LTNG’ area has met the time and width thresholds, the forecaster can use those areas to consider issuing a lightning warning if that area is over or soon to be over the 45 WS lightning warning circles. The performance of the temperature layered VIL technique compared to the original 45 WS technique and the Gremillion technique is listed in Table-5.

**TABLE-4**

Thresholds and corresponding lightning forecasts for Layered VIL above 0°C.

| THRESHOLD | LIGHTNING FORECAST |
|---|---|
| 5 mm | First flash in 15-20 min |
| > 5 mm | First flash in ~10 min |
| ≥ 7 mm | First flash is imminent |

*The IRIS radar displays VIL in units of mm, which are numerically equally to the units of Kg/m$^2$ displayed in the WSR-88D, differing only by a multiplicative factor of the density of water.*

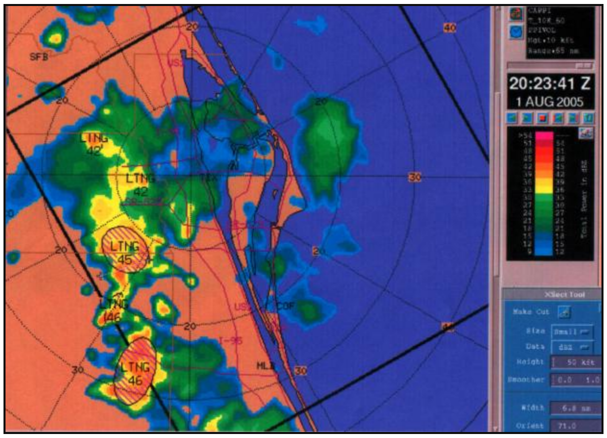

**Figure-8:** Example of the automated lightning warning product using temperature layered VIL. The black hatched areas labeled 'LTNG' are areas that have met the Layered VIL threshold for the onset of lightning. Although based on Layered VIL, the hatched area is usually displayed on the 10KFt Constant Altitude Plan Position Indicator product, to maximize the utility of limited radar display area.

**TABLE-5**

Performance of the Temperature Layered VIL technique for first cloud-to-ground lightning from a cellular thunderstorm compared to the 45 WS original, and the Gremillion technique.

| | TECHNIQUE | | |
|---|---|---|---|
| **METRIC** | **Temperature Layered VIL** | **45 WS** | **Gremillion** |
| POD | 0.92 | 0.72 | 1.00 |
| FAR | 0.29 | 0.18 | 0.29 |
| TSS | 0.26 | 0.44 | 0.31 |
| Mean Lead-time | 17.5 min | 15 min | 7.5 min |
| OUS | 0.50 | 0.48 | 0.56 |

## 5. Future Work

There are several ways the temperature layered VIL automated lightning warning product could be improved. If the actual freezing level height could be used, rather than the summer climatological height, some improvement in performance should result, especially during the infrequent lightning events with strong cold fronts during the winter.

Another way to improve the tool is to use the temperature of glaciation in a thunderstorm rather than 0°C. In a strong convective updraft, some supercooling will occur before glaciation occurs and the electrification process begins, leading to the onset of lightning. Using a temperature colder than 0°C in the temperature layered VIL would allow for that super saturation. The actual temperature to use would have to be empirically tuned, but presumably lies between 0°C and -5°C.

The tool only indicates the location where lightning initiates. It doesn't indicate area over which that lightning will strike. Using the distribution of cloud-to-ground strike distances, probabilistic lightning warning radii around each range gate where lightning is expected could be displayed, usually resulting in irregular areas of lightning threat levels around the core of the developing thunderstorm. The distribution of cloud-to-ground strike distances from the point of origin in the thunderstorm in east central Florida was developed by McNamara (2002).

Algorithms to account for other criteria in the lightning aloft in cellular thunderstorms could be added, e.g. duration, continued intensification, and width. However, the WARN product in the current version of IRIS does not support those features.

One study indicated that two simultaneous temperature layered VILs provide better forecast performance than the single temperature layered VIL currently in use (D'Arcangelo, 2000). The temperature layers and VIL thresholds are listed in Table-6. The performance of the dual temperature layered VIL technique compared to the (single) temperature layered VIL and other techniques is listed in Table-7. The dual temperature layered VIL technique was tuned to optimize the Operational Utility Score (OUS), not the more traditional approach of optimizing skill as in the other techniques, so comparing the OUS and TSS for the dual temperature layered VIL technique to the other techniques is problematic. However, even though the dual temperature layered VIL technique was not optimized for skill, it still had the highest TSS of all the four techniques reviewed here. Unfortunately, although the dual temperature layered VIL technique produced the best OUS, making it a prime candidate for 45 WS applications once lead-times are considered, this technique is not used due to the difficulty of implementing it in the IRIS radar display and analysis software.

The good performance of the dual temperature layered VIL technique suggests that a new single temperature layered VIL technique should be considered. Perhaps VIL above -10°C with a threshold ≥ 0.75 mm would perform better. This threshold was taken from summing over the two layers in the dual temperature layered VIL technique (Table-6) and assuming little VIL would usually occur above the -20°C level. This threshold would need to be empirically verified and tuned as necessary.

Although not a lightning prediction tool itself, optimizing the radar scan strategy can improve lightning forecasting. The 45 WS already uses a scan strategy that uses the appropriate climatological temperature levels to improve lightning prediction and other 45 WS applications (Roeder and Short, 2009). A new temperature adaptive scan strategy is being developed to adapt the scan strategy to temperature profiles as they evolve (Carey et al., Roeder et al., 2009a). This should improve lightning forecasting by 45 WS even further, especially during the infrequent lightning associated with winter cold fronts, when the freezing level is more variable than during the summer.

**TABLE-6**

The temperature layers and VIL thresholds for the dual temperature layered VIL technique.

| TEMPERATURE LAYER | VIL THRESHOLD |
|---|---|
| -10°C to -15°C | ≥ 0.50 mm |
| -15°C to -20°C | ≥ 0.25 mm |

**TABLE-7**

Performance of the Dual Temperature Layered VIL technique for first cloud-to-ground lightning from a cellular thunderstorm compared to the temperature layered VIL, the 45 WS original, and the Gremillion (1999) technique. The dual temperature layered VIL technique was tuned to optimize OUS, while the other techniques were tuned to optimize TSS.

| | TECHNIQUE | | | |
|---|---|---|---|---|
| METRIC | Dual Temp. Layer-ed VIL | Temp. Layer-ed VIL | 45 WS | Gremill-ion |
| POD | 0.96 | 0.92 | 0.72 | 1.00 |
| FAR | 0.21 | 0.29 | 0.18 | 0.29 |
| TSS | 0.51 | 0.26 | 0.44 | 0.31 |
| Mean Lead-time | 9.6 min | 17.5 min | 15 min | 7.5 min |
| OUS | 0.62 | 0.50 | 0.48 | 0.56 |

Others may be interested in implementing automated radar lightning warning products, such as perhaps in the WSR-88D network. While the temperature layered VIL technique works well, other techniques might give acceptable performance and be much easier to automate, e.g. the lightning prediction technique developed by Gremillion (Gremillion and Orville, 1999). In addition, more recent and on-going research on radar prediction of lightning needs to be considered (Yang and King, 2010).

Dual polarization radar has the potential to provide significantly better lightning prediction than traditional weather radar, e.g. $Z_{DR}$ towers and $\rho_{hv}$ columns (Carey et al., 2009b; Wiebke et al., 2009; Woodward et al., 2011)). Future efforts to develop automated radar lightning prediction products would be better spent on these dual polarization techniques. The 45 WS could benefit from these new automated techniques since they are acquiring a new dual polarization radar (Roeder and McNamara, 2009), which is expected to begin operational support in late 2010.

## 6. Summary

Lightning warnings are one of the many weather support products provided by 45 WS in support of America's space program at CCAFS/KSC. The 45 WS developed several techniques to forecast lightning. The latest technique uses temperature layered VIL to provide a graphical based automated warning guidance for lightning warnings. The future of radar-based lightning forecasting is most likely dual polarization radar techniques.

## 7. Acknowledgments

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