3A.7 TOOLS USED BY THE SPACEFLIGHT METEOROLOGY GROUP TO EVALUATE THE SPACE SHUTTLE WEATHER FLIGHT RULES FOR LANDING FORECASTS

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1. INTRODUCTION

The National Weather Service (NWS) Spaceflight Meteorology Group (SMG) provides meteorological support for NASA's human spaceflight program at Johnson Space Center (JSC). This includes providing weather forecasts for potential emergency post-launch abort landings and planned End-Of-Mission (EOM) landings (Brody et al, 1997). The Landing Site Weather Criteria section of the Space Shuttle Operational Flight Rules (NASA/JSC, 2006) describes the acceptable weather conditions for landing the Space Shuttle Orbiter.

Interpreting the Weather Flight Rules and the accompanying weather definitions in real-time can be quite challenging. Therefore, SMG uses various tools to aide the forecasters in determining the observed weather conditions and the trends in the observed conditions as they relate to the Weather Flight Rules. Some of these tools were developed locally while other "tools" take advantage of existing applications in the Advanced Weather Interactive Processing System (AWIPS) to help with flight rule evaluation.

This paper will cover the various tools that SMG uses to evaluate the Space Shuttle Weather Flight Rules. Following a brief discussion of the flight rules, several example tools will be shown. In addition to the benefits, challenges and limitations will be addressed. At the conclusion, a brief summary will be presented.

2. FLIGHT RULES AND DEFINITIONS

2.1 Flight Rules

Previous publications have made reference to the Space Shuttle Weather Flight Rules. For example, Garner et. al. (1997) described Weather Flight Rules as they existed in 1997, Garner and Oram (2000) covered the flight rules related to lightning avoidance and Bellue et. al. (2005) discussed how the rules have evolved over time. While not all of the Weather Flight Rules will be covered in this paper, a summary of the Weather Flight Rules that are applicable to daylight, End-Of-Mission (EOM) landings at the Kennedy Space Center (KSC) Shuttle Landing Facility (SLF) is listed in Table 1. It should be noted that flight rules vary depending on landing site, day vs. night, type of landing, and mission duration.

PARAMETER	LIMITS
Cloud Ceiling Height	>= 8,000 ft
Visibility	>= 5 statute miles
Crosswind	<= 15 kts
Headwind	<= 25 kts
Tailwind	<= 15 kts (peak) <= 10 kts (2-minute avg)
Average vs. Peak wind	<= 10 kt difference
Precipitation	Not within 30 nm
Thunderstorm, including anvil cloud	Not within 30 nm
Turbulence	<= Moderate
Detached non-transparent Anvil < 3 hours old	Not within 20 nm

Table 1. Summary of Daylight EOM Weather Flight Rules for KSC

2.2 Flight Rule Weather Definitions

The flight rule weather definitions are used to evaluate the Weather Flight Rules. Many of the weather definitions are critical when determining if the currently observed regions of interest contain clouds, precipitation, thunderstorms, and/or thunderstorm anvils. The flight rule weather definition of precipitation is defined as radar reflectivity of 18 dBZ or greater. Flight rule weather definitions state that cumulonimbus clouds (-20 degrees C or colder within any part of the convective cloud) are to be treated like a thunderstorm. The maximum reflectivity that represents the cloud edge according to the weather definitions is 0 dBZ. Understanding observed weather conditions is

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important since most of the Weather Flight Rules call for not only a GO forecast, but GO observed conditions at final decision time (approximately 10 minutes prior to launch and 90 minutes prior to landing). In the sections to follow, flight rule weather definitions will be denoted in *italics*.

3. FLIGHT RULE TOOLS

3.1 Crosswind/Headwind/Tailwind Tools

Monitoring the winds at potential landing sites is of great concern to SMG. Runway orientation and the direction and speed of the winds determine whether the winds are a crosswind, headwind, or tailwind flight rule violation (see Table 1). Wind tower networks have been established at the 3 Primary Landing Sites (PLS): (1) Shuttle Landing Facility (SLF) at Kennedy Space Center, Florida (KSC), (2) Edwards Air Force Base, California (EDW), and (3) Northrup Strip (NOR) at White Sands, New Mexico. Data from these networks are ingested into the Johnson Space Center (JSC) Meteorological Interactive Data Display System (MIDDS), a McIDAS based software system used by SMG. The MIDDS decodes the wind tower data and stores the data in McIDAS Meteorological Data (MD) format.

Figure 1 shows a screen shot from the WINDS display in MIDDS. The example shown is for the wind towers at EDW. A "map" of the runways and the location of each wind tower are depicted on the left hand side of the display and a text listing of the wind tower data from each runway's wind towers is on the top right hand side. The winds that are in violation of the flight rules are denoted by the yellow text boxed with red background. For example, tower 150 (relative to runway 05) and tower 044 (relative to runway 04) are violating both the average and peak tailwind limits. Tower 180 (relative to runway 18) is violating the crosswind limit.

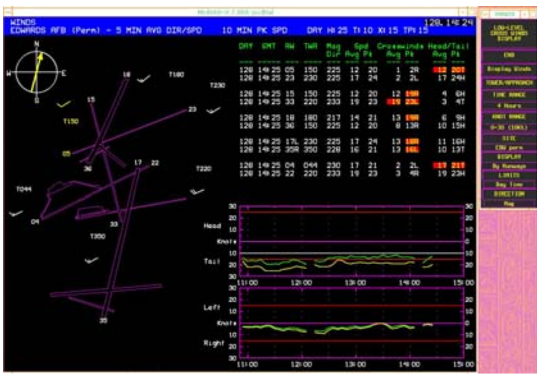

Figure 1. WINDS display

The WINDS display also allows for time series plots to be displayed for each tower/runway approach in order to graphical depict trends. In the example in Figure 1, tower 150/approach runway 05 was selected (as denoted by the yellow text in the "map" on the left hand side) and the resulting time series plot is shown in the bottom right hand side of the display.

Another tool that SMG uses to aide in wind forecasts is the SLF Peak Wind application. This is a PC-based Graphical User Interface (GUI) that was developed by the NASA Applied Meteorology Unit (AMU) to display the SLF peak wind speed climatologies and probabilities (Lambert, 2003). This tool can be very useful operationally when SMG is issuing surface wind forecasts. SMG is required to issue both average and peak wind forecasts. While numerical weather prediction models and Model Output Statistics (MOS) can give insight for average wind speed and direction, peak wind guidance is limited. The SLF Peak Wind tool provides the forecasters with an easy point and click interface (see Figures 2a) for inputting the expected average speed and getting in return (see Figure 2b) the probabilities of various peak speeds based on the input average speed.

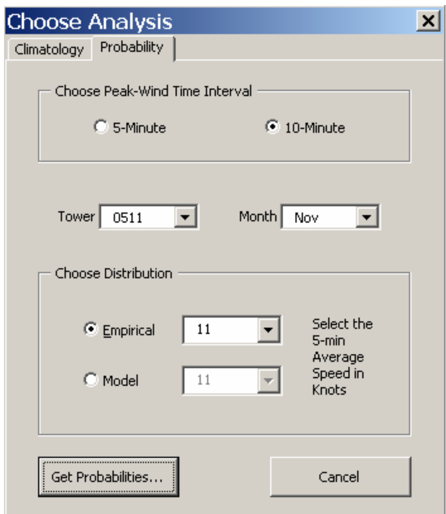

Figure 2a. Peak Wind input GUI. Users choose a tower, month, and 5-minute average speed from the drop down menus.

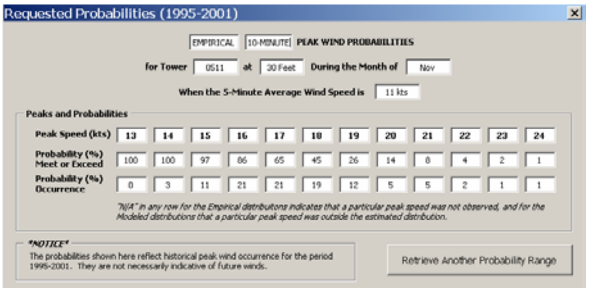

Figure 2b. Peak Wind output GUI. Probabilities of peak winds corresponding with tower, month, and average speed from 2a are displayed.

3.2 Precipitation and Cloud Temperature Tools

SMG has customized color table enhancements to help with flight rule evaluation. Figure 3 is an example 0.5 degree radar reflectivity image. The reflectivity enhancement that is shown is the default enhancement that SMG uses operationally. The dBZ ranges defined by the radar reflectivity enhancement correspond with many of the flight rule weather definitions. Per the flight rule weather definitions, the maximum radar reflectivity that represents a *cloud top* or *cloud edge* is 0 dBZ. *Non-transparent* clouds are defined as 0 dBZ or greater while *precipitation* is 18 dBZ or greater. Therefore, the radar reflectivity enhancement allows SMG to easily differentiate between non-transparent clouds (light blue) and precipitation (green).

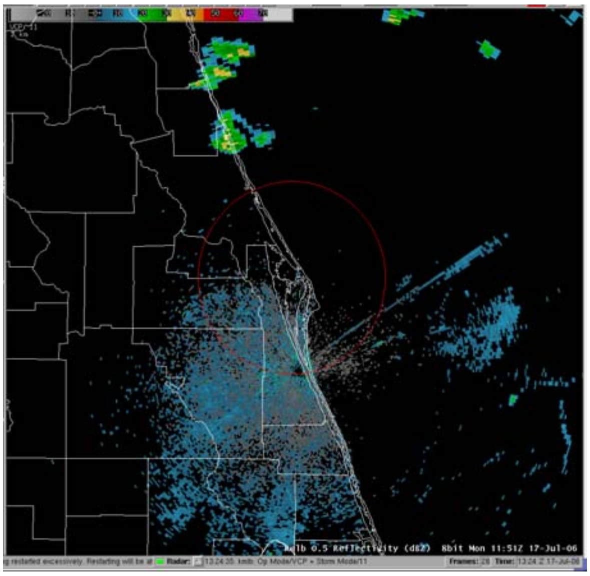

Figure 3. Radar enhancement

The enhancement also highlights the intensity of precipitation. Weather definitions for precipitation intensity are:

- 18 dBZ ≤ *light precipitation* < 30 dBZ
- 30 dBZ ≤ moderate *precipitation* < 38 dBZ
- *heavy precipitation* ≥ 38 dBZ

The colors in the enhancement table are consistent with these precipitation intensity dBZ ranges. Specifically, green denotes *light precipitation* and yellow denotes *moderate precipitation*.

The infrared satellite imagery in Figure 4 depicts another color table enhancement that SMG has customized for flight rule evaluation. This enhancement is especially useful in identifying thunderstorms. The weather definitions state: “Any convective cloud with any part colder than -20 degrees C shall be considered a cumulonimbus cloud and treated like a *thunderstorm* for flight rules purposes.” (NASA/JSC, 2006). The satellite enhancement clearly depicts cloud top temperatures colder than -20 degrees C (and thus a thunderstorm by flight rule definition) as the darker colors (blue, dark blue and black).

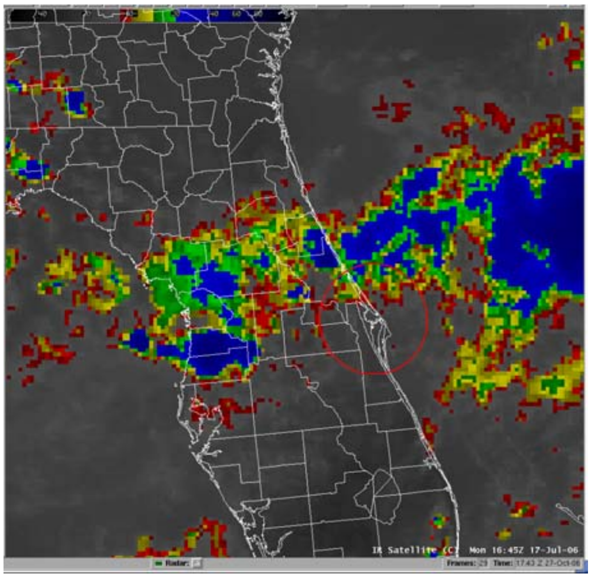

Figure 4. Satellite enhancement

The satellite enhancement is also a very useful tool to use when SMG is evaluating the “RTLS rainshower rule”. Recall from Table 1 that there can be no precipitation within 30 nm of KSC for End-Of-Mission. For a Return To Launch Site (RTLS) landing at KSC (a **post-**

launch abort scenario), there can be no precipitation within 20 nm. However, under certain conditions, the "RTLS rainshower rule" can be invoked to allow for precipitation within 20 nm of the runway. The rule states rain showers are allowed, but if a rain shower (excluding cumulonimbus) has a cloud top temperature colder than +5 degrees C or has had a cloud top temperature colder than -10 degrees C within 2 1/2 hours prior to launch, the orbiter must avoid that shower by 10 nm laterally or 2 nm vertically.

The satellite enhancement allows SMG to evaluate the cloud tops as they relate to the "RTLS rainshower rule". First, the rule states that the showers must not be cumulonimbus, so any cloud tops that contain the darker colors (blue, dark blue, and black) cannot be considered for the rule. Second, the showers with cloud tops colder than +5 degrees C can be easily tracked since they would be red, yellow, or green. Third, the showers with cloud tops colder than -10 degrees C can be narrowed down by simply focusing on the green.

3.3 Fog Visualization Tools

The detection and forecasting of fog is important for evaluating the visibility constraints in the flight rules. To assist SMG with fog visualization, satellite and mesoscale gridded analysis products are used.

The NOAA Satellite Services Division (Ellrod, 1995) has developed a fog product utilizing the difference in emitted radiation between the 11.0 and 3.9 micrometer channels on the GOES imager. This product is distributed through NOAAPort and available for display in AWIPS. SMG has found that brightness values of -5 tend to be a good first guess for areas of fog and low ceilings. Therefore, a satellite enhancement has been created that depicts brightness values less than -5 as green. An example of the fog product from 2 November 2006 at 1100 UTC using this enhancement is shown in Figure 5a. The visible image from 1400 UTC on the same day is shown in Figure 5b. The "green" areas in Figure 5a provide an indication of the fog over Central Florida extending into the vicinity of Kennedy Space Center.

SMG has implemented the Advanced Regional Prediction System (ARPS) model to provide mesoscale forecasts (Oram et. al, 2004). The ARPS Data Analysis System (ADAS) provides SMG with an analysis tool and the output of ADAS is used to initialize the ARPS model. ADAS provides an integrated analysis of all available data in the vicinity of Kennedy Space Center including surface observations, satellite imagery, weather radar, and mesonet data. This analysis can be used to diagnose the atmosphere for nowcasting and to monitor current conditions. One application of the data is the routine calculation of the Fog Stability Index (FSI) and display of the index with the dew point depression (Figure 6). Forecast studies have shown FSI values of less than 31 indicate a high risk of fog formation, 31 to 55 a moderate risk, and greater than 55 a low risk of fog formation (Air Weather Service, 1990). The FSI display is available to forecasters via the web (http://www.srh.noaa.gov/smg/adas_realtime.html) and the analyses are available in AWIPS.

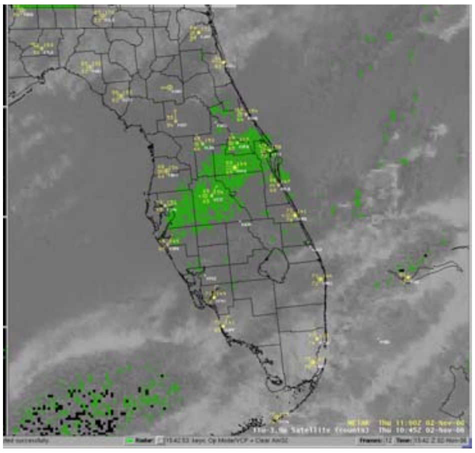

Figure 5a. Fog Product from 1100 UTC on 2 November 2006

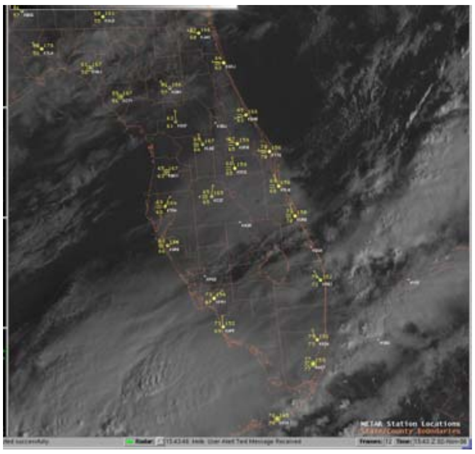

Figure 5b. Visible Satellite from 1400 UTC on 2 November 2006

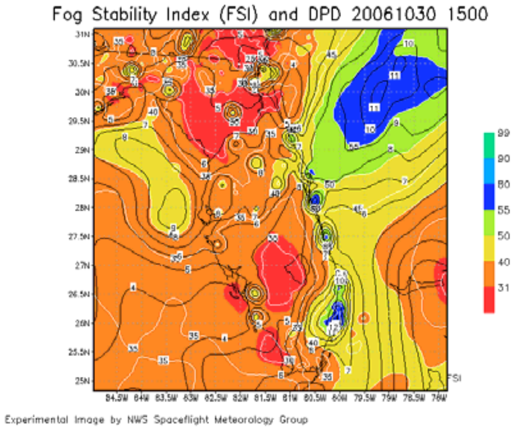

Figure 6. ADAS Fog Stability Index and Dew Point Depression

3.4 Anvil Transparency Tools

Determining anvil transparency is critical when evaluating thunderstorm related flight rules. The rules stipulate that any *non-transparent anvil*, whether attached or detached from a parent thunderstorm, be treated as a *thunderstorm* utilizing standard thunderstorm avoidance criteria (See Table 1). Visual observations, either from a surface based observer or a pilot, are not always available during launch or landing countdowns to make this determination. Visible satellite imagery can offer some assistance in determining anvil transparency during daylight hours but is ineffective during the night when only infrared imagery is available (Fig 7). For this reason radar data has become SMG's primary data source for determining anvil transparency. Since a radar return of 0 dBZ has been defined as the *cloud edge*, it can also be used as the transition point from *transparent* to *non-transparent* (Krider et. al, 1999).

Radar reflectivity greater than 0 dBZ on the Layer Reflectivity Max (LRM) mid- and high-level products has been found to correspond reasonably well with the *non-transparent* edge of anvils (Short and Wheeler, 2004). The LRM products are available from 88D radars via one-time or multiple requests (Figures 8 and 9). However, the absence of radar reflectivity in these products does not mean the cloud is *transparent*. Therefore, the LRM products are useful in identifying areas that are likely *non-transparent* allowing a human observer in a weather reconnaissance to evaluate those anvils clouds whose transparency is ambiguous.

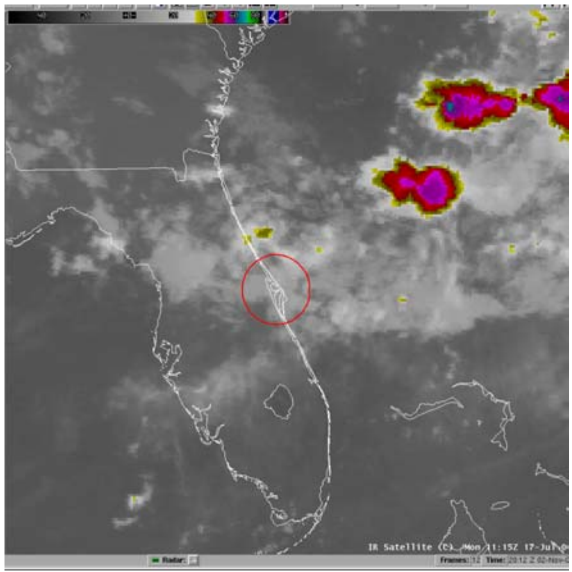

Figure 7. Infrared satellite imagery - July 17, 2006 1115Z used to evaluate thunderstorm anvil 50 miles north of KSC near KDAB

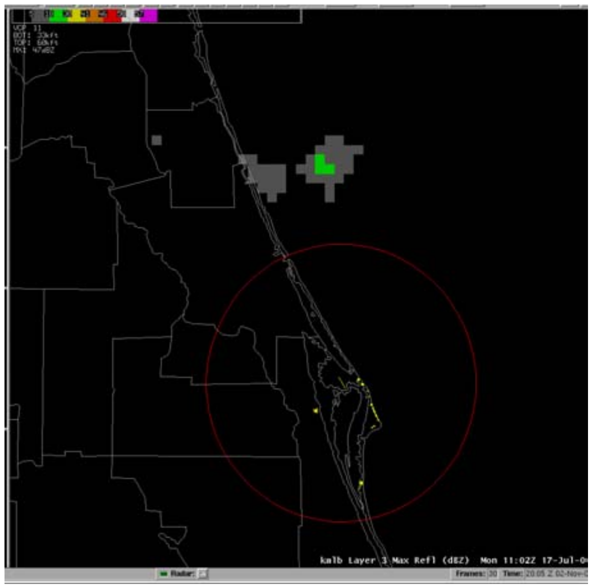

Figure 8. Layer Reflectivity Maximum – Mid from KMLB July 17, 2006 1102Z. Reflectivities depicted are > 5 dBZ.

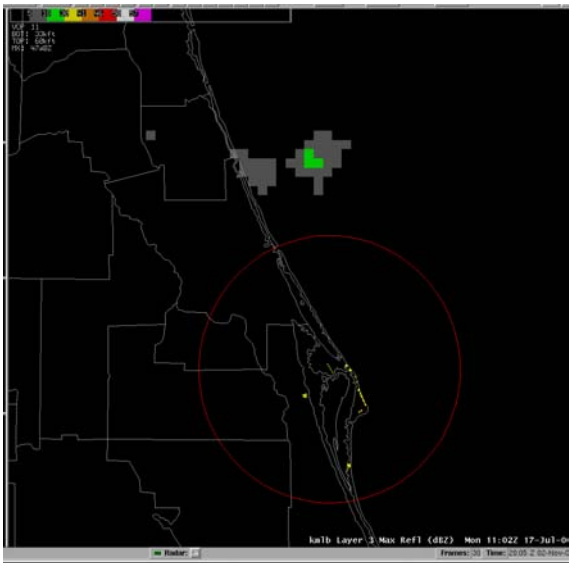

Figure 9. Layer Reflectivity Maximum – High from KMLB July 17, 2006 1102Z. Reflectivities depicted are > 5 dBZ.

In addition, when a User Selectable Layer (ULR) product (with its higher resolution and ability to display negative dBZ returns) is requested for a layer including the anvil, it can be even more effective at distinguishing transparency (Figure 10). Combining these radar data with visible or IR imagery on AWIPS allows for easy comparison of the two data sources for evaluating anvil transparency.

Figure 10. User Selectable Layer from KMLB July 17, 2006 1102Z. Reflectivities depicted are > 0 dBZ.

3.5 Natural and Triggered Lightning Tools

A program to continuously display weather parameters relevant to flight rule evaluation of natural and triggered lightning is shown in Figure 11. The display program makes TCP/IP requests for data from the MIDDS, but displays the data using a graphical user interface and display written in tcl/tk. The display program provides information regarding cloud-to-ground lightning locations from the National Lightning Detection Network, significant weather from METARs, and electric field values from the CCAFS/KSC field mill network. Lightning within certain distances of the SLF is prohibited by the flight rules. The display provides this information from the NLDN as well as reports of thunderstorms or showers from the METARS. In addition, the field mills detect anomalous electrification of the atmosphere. Although there is no specific flight rule related to electric field measurements, the information can provide forecasters important information for maintaining situational awareness of the potential for natural or triggered lightning.

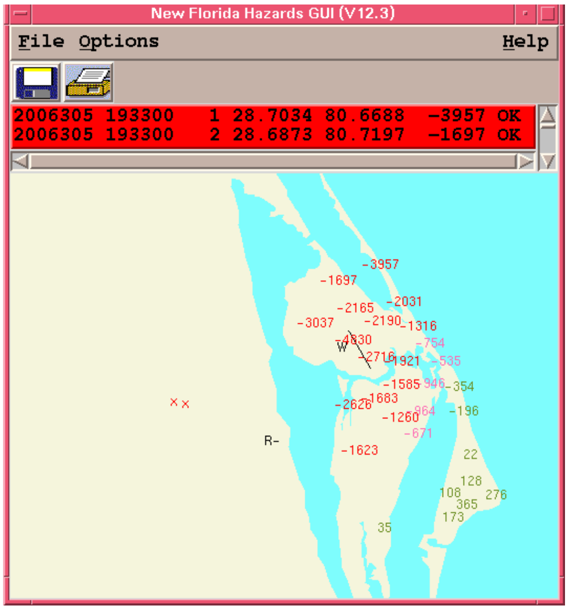

Figure 11. Florida Hazards Program displaying NLDN lightning locations (red "x"), significant weather from METARs (text in McIDAS weather code), and color coded electric field values from the CCAFS/KSC field mill network. The text in the window above the plan-view display of the data lists field mill values from the network.

3.6 METAR and TAF Tool

Surface Observations and Terminal Aerodrome Forecast (TAF) text for various potential landing sites is displayed in an independent application (See Figure 12). The surface observations and TAFs are stored in MIDDS datasets. The tcl/tk application polls these datasets and scans for flight rule violations which are highlighted in red in the GUI. The flight rules can be configured depending on the phase of the mission (RTLS, EOM, etc.). In addition, various pre-defined sites can be displayed or the forecaster can choose to manually choose other locations.

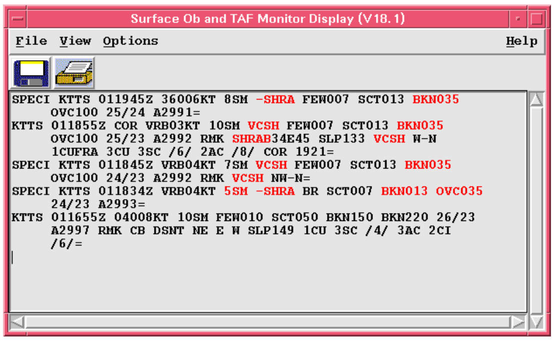

Figure 12. Surface Observation and TAF Monitor Display. Flight rule violations are highlighted in red.

4. CHALLENGES AND LIMITATIONS

SMG forecasters are presented with challenges when using the flight rule tools. One challenge is to remember that many of the tools are useful for the observed conditions, but may not tell you much about the forecasted conditions. While trends are valuable, they can not always be linearly extracted to give future conditions. None of the flight rule tools can reliably account for convective initiation and other mesoscale features.

Trying to simply view all of these flight rule tools can be a challenge since the applications exist on a wide variety of display systems. Many of the tools can be integrated easily in AWIPS, however, some are outside of AWIPS. Some of the tools work within the MIDDS environment (e.g. WINDS, Surface Ob and TAF GUI, Florida Hazards GUI) while others are PC-based (e.g. SLF Peak Wind Tool, ADAS Fog Stability Index web product).

Besides the challenge of integrating the tools, there are many limitations with the various flight rule applications. For example, the satellite enhancement (Figure 4) should be used with extreme caution. There is no way to tell from this cloud top temperature enhancement alone the cloud **types**. Specifically, the cold cloud top temperatures (-20 C or less) could simply be from high level cirrus clouds rather than cumulonimbus or thunderstorm anvil clouds. Other evaluation techniques must be used in conjuction with this enhancement to determine the cloud types. During daylight, the visible satellite can very useful for determining cloud types, however, at night, visible satellite is not an option. Lightning is obviously a good indicator that the clouds are thunderstorm clouds, but the true value of the satellite enhancement is to highlight cumulonimbus clouds that may not have cloud-to-ground lightning associated with them.

The LRM (Figures 8 and 9) and ULR (Figure 10) radar products present challenges and limitations as well. These tools are severely limited by the radar's cone of silence, meaning that weather phenomena close to the radar cannot be sampled. A benefit of the ULR product, however, is that the cone of silence is clearly depicted by the "donut hole". This is not the case with the LRM products.

5. SUMMARY

The NWS Spaceflight Meteorology Group must adhere to the Space Shuttle Weather Flight Rules. Understanding observed weather conditions and how they relate to the flight rules is important since most of the Weather Flight Rules call for not only a GO forecast, but GO observed conditions. Interpretation of the current weather scenario and its relationship to many of the flight rules can be quite difficult just using standard radar, satellite, and lightning displays. Therefore, SMG uses various tools to aide in the evaluation of flight rules. The flight rule tools have proved to be quite useful for observed conditions, but using the tools alone is not sufficient. Understanding the meteorological aspects of the weather phenomena remains an important focus to SMG operations.

Notice

informing the reader of the resources used to conduct the work reported herein.

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