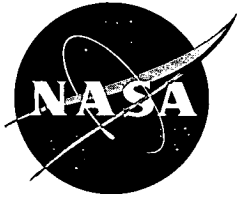


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Stable Low Cloud Phase II: Nocturnal Event Study

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Executive Summary

This report describes the work done by the Applied Meteorology Unit (AMU) in developing a database of nights that experienced rapid (< 90 minutes) low cloud formation in a stable atmosphere, resulting in ceilings at the Shuttle Landing Facility (TTS) that violated Space Shuttle Flight Rules (FR). This work is the second phase of a similar AMU task that examined the same phenomena during the day. In the first phase of this work, the meteorological conditions favoring the rapid formation of low ceilings include the presence of any inversion below 8000 ft, high relative humidity (RH) beneath the inversion and a clockwise turning of the winds from the surface to the middle troposphere (~15000 ft). The AMU compared and contrasted the atmospheric and thermodynamic conditions between nights with rapid low ceiling formation and nights with low ceilings resulting from other mechanisms. The AMU found that there was little to discern between the rapidly-forming ceiling nights and other low ceiling nights at TTS. When a rapid development occurred, the average RH below the inversions was 87% while non-events had an average RH of 79%. One key parameter appeared to be the vertical wind profile in the Cape Canaveral, FL radiosonde (XMR) sounding. Eighty-three percent of the rapid development events had veering winds with height from the surface to the middle troposphere (~15,000 ft) while 61% of the non-events had veering winds with height. Veering winds indicate a warm-advection regime, which supports large-scale rising motion and ultimately cloud formation in a moist environment. However, only six of the nights (out of 86 events examined) with low cloud ceilings had an occurrence of rapidly developing ceilings. Since only 7% rapid development events were observed in this dataset, it is likely that rapid low cloud development is not a common occurrence during the night, or at least not as common as during the day. In the AMU work on the daytime rapid low cloud development (Case and Wheeler 2005), nearly 30% of the low cloud ceiling cases investigated were identified as rapidly developing events.

Forecasters at the Space Meteorology Group (SMG) issue 30 to 90 minute forecasts for low cloud ceilings at TTS to support Space Shuttle landings. Mission verification statistics have shown ceilings to be the number one forecast challenge. More specifically, forecasters at SMG are concerned with any rapidly developing clouds/ceilings below 8000 ft in a stable, capped thermodynamic environment. Therefore, the AMU was tasked to examine archived events of rapid stable cloud formation resulting in ceilings below 8000 ft, and document the atmospheric regimes favoring this type of cloud development.

The AMU examined the cool season months of November to March during the years of 1994–2005 for nights that had low-level inversions and rapid, stable low cloud formation that resulted in ceilings violating the Space Shuttle FR. The AMU wrote and modified existing code to identify inversions from the evening and morning XMR radiosonde during the cool season and output pertinent sounding information. They parsed all days with cloud ceilings below 8000 ft at TTS, forming a database of possible rapidly-developing low ceiling events. Nights with precipitation or noticeable fog burn-off situations were excluded from the database. Only the nighttime hours were examined for possible ceiling development events since the daytime events were examined in the first phase of this work.

The report presents one sample case of rapidly-developing low cloud ceilings. The case depicts the representative meteorological and thermodynamic characteristics of such events. The case also illustrates how quickly the cloud decks can develop, sometimes forming in 30 minutes or less.

The report also summarizes the composite meteorological conditions for 6 event nights with rapid low cloud ceiling formation and 80 non-events nights consisting of advection or widespread low cloud ceilings. The meteorological conditions were quite similar for both the event and non-event nights, since both types of nights experienced low cloud ceilings. Both types of nights had a relatively moist environment beneath an inversion based below 8000 ft.

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1 Introduction

Forecasters at the Space Meteorology Group (SMG) have the responsibility of issuing Shuttle landing forecasts for standard and abort landing scenarios including

- Return to Launch Site (RTLS) abort landings at Kennedy Space Center (KSC),
- Abort-once-around at the primary landing site (KSC), and
- Standard End Of Mission at KSC, Edwards Air Force Base, CA (EDW), and White Sands Space Harbor, NM (NOR; Brody et al. 1997).

One element of these forecasts is a 30 to 90 minute forecast for low cloud ceilings at the KSC Shuttle Landing Facility (SLF, 3-letter identifier TTS) to support space shuttle landings. Mission verification statistics have shown ceilings to be the number one forecast challenge for SMG. More specifically, forecasters at SMG are concerned with any rapidly developing ceilings below 8000 ft in a stable, capped thermodynamic environment. Therefore, the Applied Meteorology Unit (AMU) was tasked to examine archived events of rapid stable cloud formation resulting in ceilings below 8000 ft, and document the atmospheric regimes favoring this type of cloud development.

In the first phase of this project (Case and Wheeler 2005), the AMU examined the cool season months of November to March during the years of 1994-2005 for days that had low-level (below 8000 ft) temperature inversions and rapid, stable low cloud formation that resulted in ceilings violating the Space Shuttle Flight Rules (NASA/JSC 2004) during daytime hours. This report focuses only on the cloud ceiling rule as applied to the KSC landing site at night as shown in Table 1.

Table 1. Space Shuttle Flight Rules for cloud ceiling heights and visibility restrictions pertaining to various landing scenarios and locations (taken from NASA/JSC 2004). The nighttime rules for a KSC landing are highlighted in yellow.					
Ceiling / Visibility (kft)/(sm)			Redundant Microwave Landing System (MLS)	Single-String MLS	No MLS
KSC, EDW, NOR, Abort Once Around, Daily Primary Landing Site (PLS) Selection (all sites)	Concrete	Day	≥8/5	≥10/7	
		Night		NO-GO	
	Lakebed	Day			≥10/7
		Night		≥15/7	NO-GO
Return To Launch Site (RTLS), Trans-oceanic Abort Landing (TAL)	Concrete	Day	≥5/5 TAL	≥10/7	
		Night	≥5/4 RTLS	NO-GO	
Augmented Contingency Landing Site / East Coast Abort Landing / Emergency Landing Site			0/0		≥8/5
Predeorbit: One Auxiliary Power Unit (APU) failed OR Attempt two APU's procedure			≥10/7		

The most commonly encountered cloud ceiling height restriction for shuttle landings is 8000 ft, which is the focus of this work. The AMU identified low-level inversions from the morning Cape Canaveral Air Force Station (CCAFS) radiosonde (3-letter identifier XMR) during the cool season and gathered the pertinent sounding information. They then parsed all days with cloud ceilings below 8000 ft at TTS, forming a database of possible rapidly-developing low ceiling events. For the first phase, an event was defined as a low cloud ceiling developing suddenly (an hour or less) in a stable environment. A non-event was a low cloud ceiling in a stable environment that occurred either as a result of the advection of low clouds or widespread cloudiness for much of the day. Days with precipitation or noticeable fog burn-off situations were excluded from the database. In the first phase of this work,

only the daytime hours were examined for possible ceiling development events since low clouds are easier to diagnose with visible satellite imagery. For the daytime cases, the distinguishing factor between the event and non-event days appeared to be the vertical wind profile in the XMR sounding. Eighty-five percent of the event days had a clockwise turning of the winds with height in the lower to middle troposphere (~ 15,000 ft) whereas 83% of the non-events had a counter-clockwise turning of the winds with height or negligible vertical wind shear.

The main objectives for the second phase of this project included:

- Create a database of rapid-developing cloud ceilings below 8000 ft during the nighttime hours,
- Identify the onset and (if applicable) dissipation times, and
- Document the atmospheric regimes favoring the rapid, stable cloud formation.

Since nighttime cases were the focus in this study, the AMU analyzed both the morning and evening soundings from the XMR radiosondes. Unlike the daytime study, days without a low-level inversion were retained to create a larger nighttime database. Similar to the daytime study, the AMU used satellite imagery to determine whether low ceilings were due to in-place cloud development or the advection of low clouds. Since the higher-resolution visible images were not available, a variety of infrared enhancements in the Meteorological Interactive Data Display System (MIDDS) developed for observing low cloud were employed to help visualize the nocturnal low clouds. This report summarizes the work done with the nighttime cases and provides a sample case from the data set.

2 Methodology

SMG indicated that they have observed nighttime rapid low cloud development events in the cool season. Therefore, the period of record (POR) for this study was the cool season months of November to March 1994-2005, for a total of 12 cool seasons. While satellite imagery is the ideal source for determining the existence of clouds, nighttime low-cloud events are difficult to identify with infrared imagery since developing low, warm clouds tend to have temperatures close to that of surface. Therefore, the AMU collected additional data from the evening and morning XMR radiosonde and hourly surface observations at TTS between 2200-1200 UTC to assist in the analysis. Due to the large number of cool-season days to examine for stable low-cloud formation, the AMU devised an objective method to retain only days with observed cloud ceilings below 8000 ft at TTS.

2.1 Sounding Availability and Parameters

Archived sounding data were obtained from Computer Sciences Raytheon for POR. The XMR soundings at 2200 and 1000 UTC were required for detecting the potential nighttime events. If one of the soundings was missing for any potential event, the date was not considered. Since the first phase of this study found low-level inversions to be an important parameter for rapid cloud development, the software developed for this phase of the work output the base, depth, and magnitude of the inversions for the soundings at 2200 and 1000 UTC. Also, the program would output data every 1000 ft from the surface to 8000 ft including altitude, pressure, wind direction, wind speed, shear, temperature, dew point, relative humidity (RH), and the mean wind direction and speed in the 8000 ft layer. These parameters were used to help narrow down the number of potential days meeting the pre-defined criteria for the study, as well as provide data for assessing potential rapid low-cloud development events.

2.2 Low Cloud Ceiling Identification

The AMU wrote software to analyze the frequency of ceilings at and below 8000 ft and 5000 ft at TTS, for the years 1994-2005. The program also determined which ceilings were due to rain or fog. Output from the program was used to identify possible events, in which low clouds developed rapidly in a stable environment.

The following criteria were used to identify the beginning of a possible event:

- No low ceilings, precipitation, or fog occurred within the three previous hours,
- An event must have started between 2200 and 1200 UTC, since only nighttime events were considered,
- Events in which high clouds would obscure low clouds were not used because it would be impossible to distinguish between low cloud rapid development and advection in the satellite imagery, and
- Events in which low clouds developed over several hours were thrown out, since only rapid development was the concern in this task.

The following criteria were used to identify the end of a possible event:

- Precipitation or fog occurred within three hours,
- Events must have ended by 1200 UTC since only nighttime events are considered, and
- The ceilings dissipated or rose to above 8000 ft.

2.3 Database of Possible Events

A subjective analysis of the output from the identification of low-level inversions and ceilings described in Section 2.2 was conducted to identify potential case days. The database was further filtered to exclude events with reports of showers or showers in the vicinity of the TTS observation. At this point in the analysis, 360 total events were identified – about 30 possible events per year. Of those 360 possible events, the AMU possessed infrared satellite imagery for 48. However, only 37 of the possible events with archived infrared satellite imagery had both a 2200 and 1000 UTC XMR sounding. The AMU ordered additional satellite imagery from the NOAA Comprehensive Large Array-data Stewardship System (CLASS) archive for possible events in which archived satellite imagery were missing. Unlike the archived AMU satellite imagery, the CLASS infrared satellite imagery was generally only available in 30-minute increments. By adding the CLASS satellite imagery to the dataset, a total of 86 possible events were identified for the years 2000-2005. Based on the number of cases and events in the first

phase of this work, the AMU decided not to obtain additional satellite imagery and focus time and effort analyzing the 86 possible events.

2.4 Infrared Satellite Imagery Analysis

The only way to confirm whether or not a possible event was an in-place rapidly developing ceiling rather than cloud advection was to examine the satellite imagery. The AMU first restored archived infrared satellite imagery onto the Meteorological Interactive Data Display System (MIDDS), then downloaded and loaded the CLASS satellite imagery onto MIDDS. All imagery was viewed with MIDDS software and images were saved in JPEG format. Finally, after examining satellite imagery for all 86 possible events, there were only 6 identified as rapid possible low-cloud formation events. The remaining 80 possible events were clearly advection situations. The infrared satellite imagery was sufficient to identify advection cases but was of marginal use to identify rapidly developing cases. It was very difficult to identify and label the 6 cases in this task as rapidly developing.

3 8 January 2004 Event

The rapid low cloud development in this case began on 8 January at 2343 UTC and ended 9 January at 0400 UTC. The 1200 UTC surface analysis on 8 January (Figure 1) showed Florida weather was controlled by a high pressure system centered over northern South Carolina. By 1200 UTC on 9 January (Figure 2), the high pressure system was no longer present and a stationary front was located across north Florida. This pattern resulted in a stable atmosphere across central Florida with a light northerly surface wind at KSC/CCAFS. The 2200 UTC sounding from XMR on 8 January showed a relatively low-level moist layer from 900 to 860 mb and a strong inversion with a base at 860 mb and a top at 820 mb with a strength of 4.1 °C (Figure 3). The winds below the inversion were light northerly at the surface, veered to northeast near the top of the inversion, and then backed to the west northwest above the inversion. The average layer RH from the surface to 820 mb (7000 ft) was 67%. The 1000 UTC 9 January sounding at XMR (Figure 4) showed high moisture in the low-levels, except for a dry layer between 850 and 825 mb. There was an inversion between 851 and 836 mb with a strength of 2.0 °C which was weaker than the inversion observed in the 2200 UTC sounding. Winds gradually veered with height from south southwest at the surface to west near the inversion base. The average layer RH from the surface to 836 mb (6000 ft) was 84%.

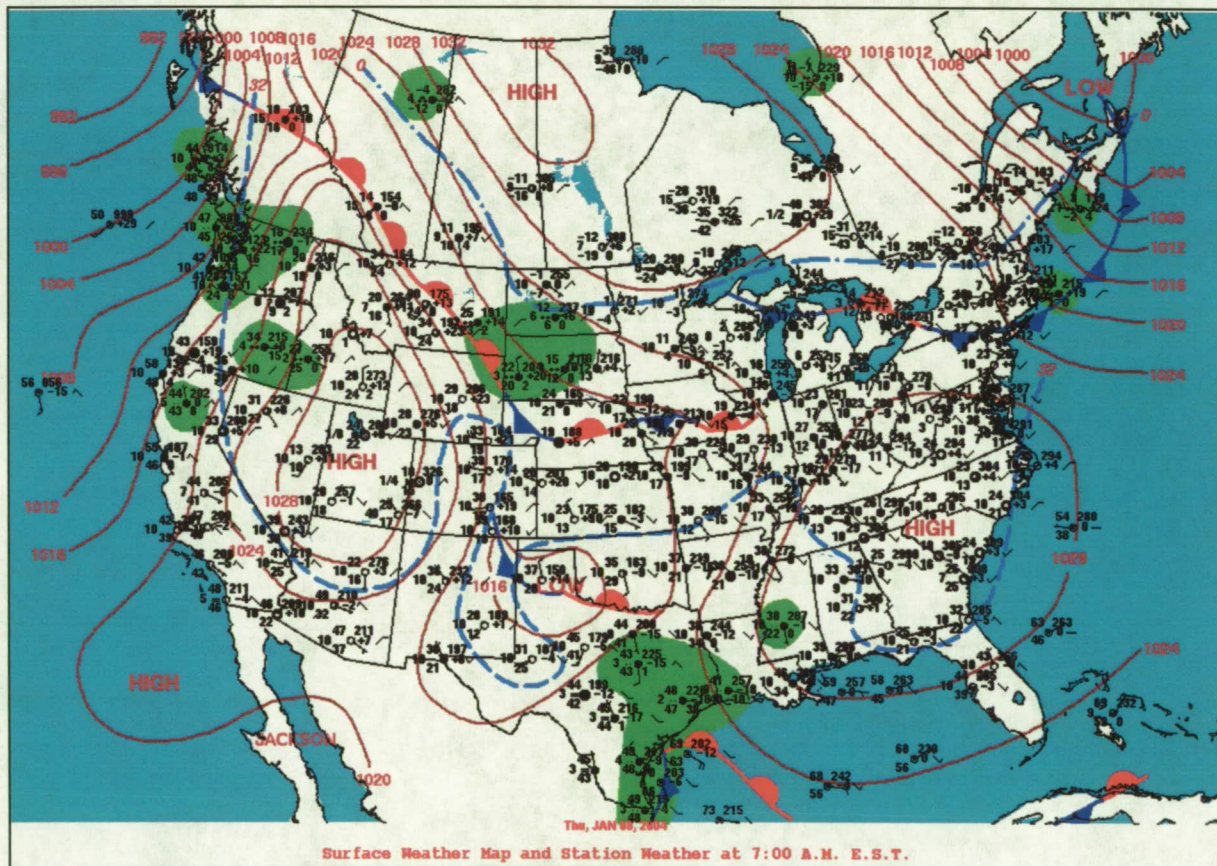


Figure 1. Surface analysis at 1200 UTC 8 January 2004.

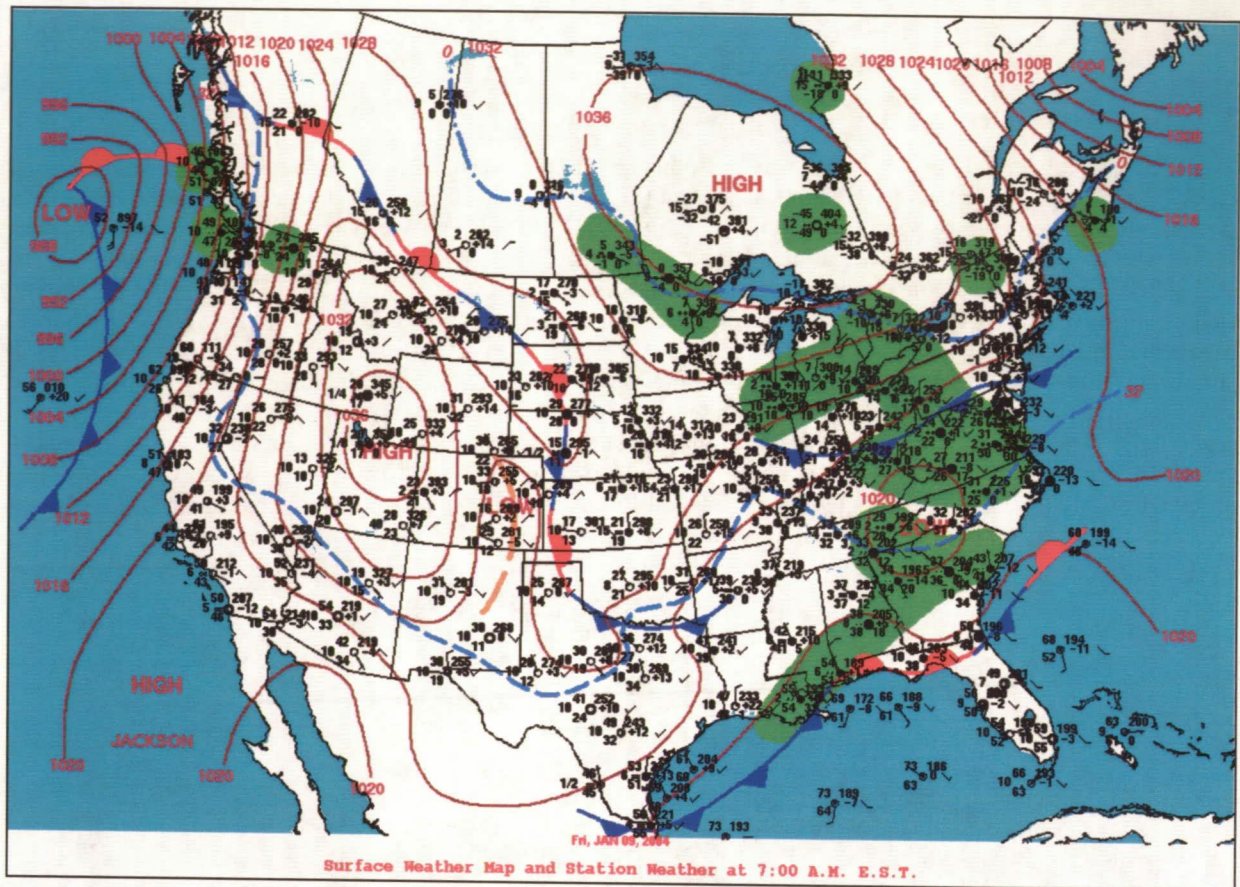


Figure 2. Surface analysis at 1200 UTC 9 January 2004.

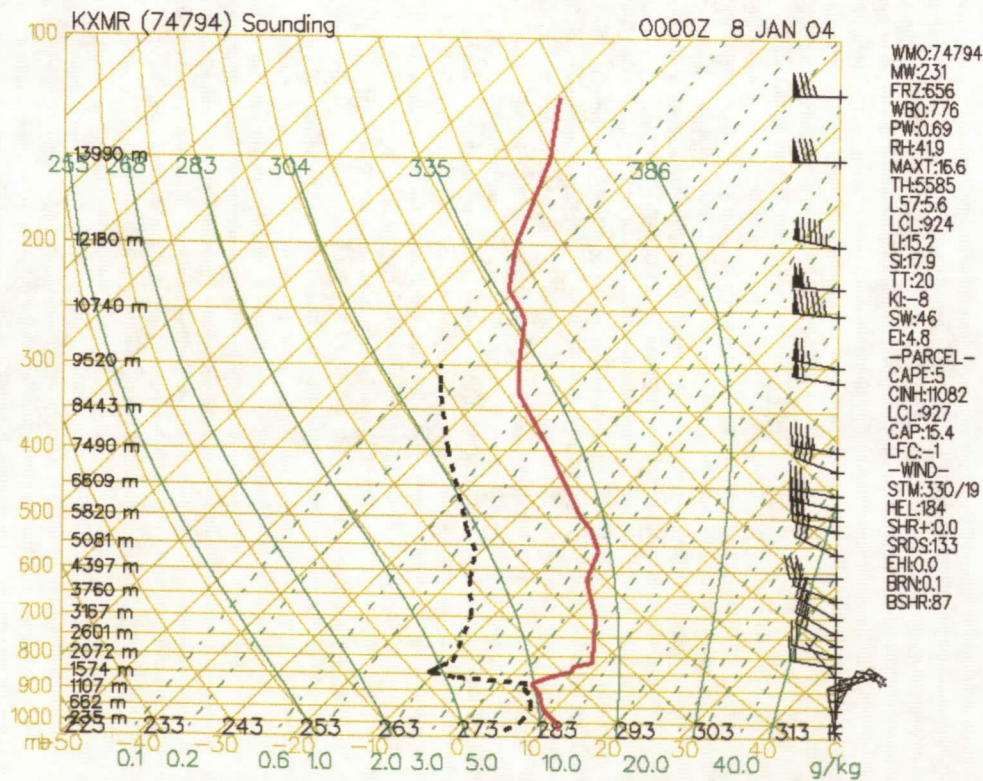


Figure 3. XMR sounding at 2200 UTC 8 January 2004.

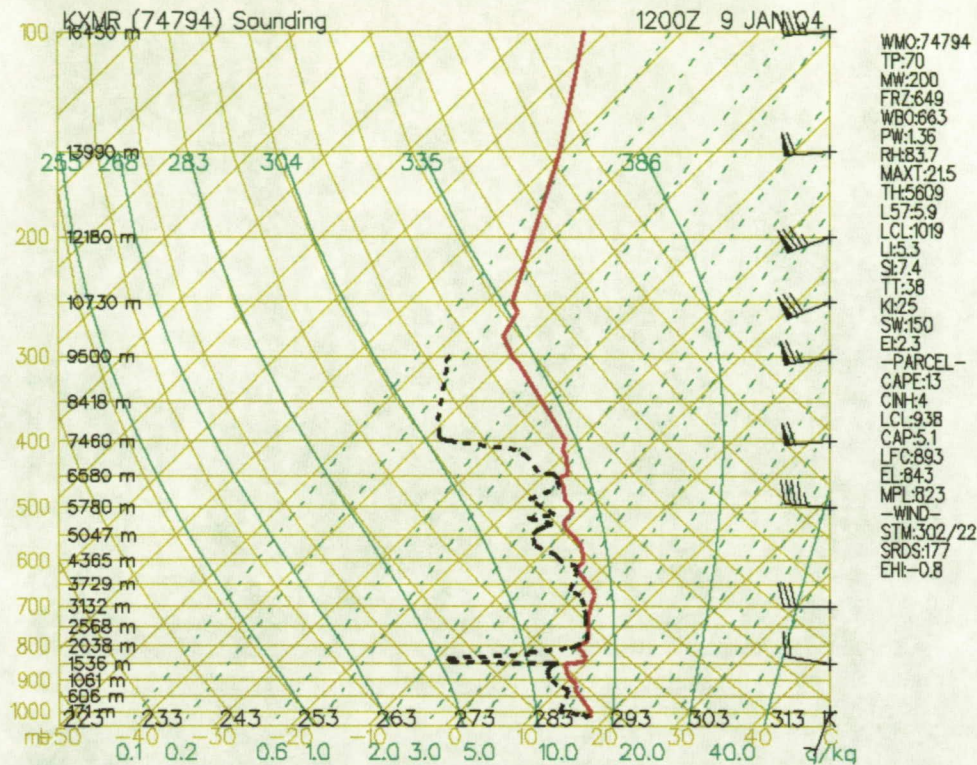


Figure 4. XMR sounding at 1000 UTC 9 January 2004. The low-level inversion had weakened, however winds still veer from the surface to the top of the inversion.

A series of infrared satellite images are presented in Figures 5-8. Although it is difficult to see from the static images in this report, viewing a loop of the images revealed low-level clouds east-southeast of KSC/CCAFS moving slowly westward followed by a sudden rapid development of the clouds over KSC/CCAFS in the 30-minute period from 2232 UTC to 2302 UTC on 8 January. By viewing the loop of satellite images, it appeared as if the clouds “jumped northward” as they rapidly developed over KSC/CCAFS. Since the low cloud area is so difficult to discern in this report, the low cloud area in each figure is outlined with a white line to assist the reader. A figure-by-figure description of the satellite imagery follows.

At 2202 UTC on 8 January, high clouds showing as bright white were evident over north Florida and Georgia while an area of low clouds depicted as dark gray were found to the east-southeast of the KSC/CCAFS area in the Atlantic Ocean moving slowly westward (Figure 5). Skies at KSC/CCAFS were clear. Thirty minutes later, at 2232 UTC, skies were still clear near the SLF (Figure 6) while the area of low clouds continued to move west. By 2302 UTC, however, low clouds had developed rapidly over the KSC/CCAFS area just south of the SLF (Figure 7). It is between the images in Figures 6 and 7 that the low clouds appear to “jump” northward as indicated by viewing the loop of the satellite imagery while the rest of the low cloud area continues to move slowly west. By 2332 UTC, 11 minutes before a 4,400 ft ceiling was reported at the SLF and the low clouds had covered almost the entire KSC/CCAFS area (Figure 8).

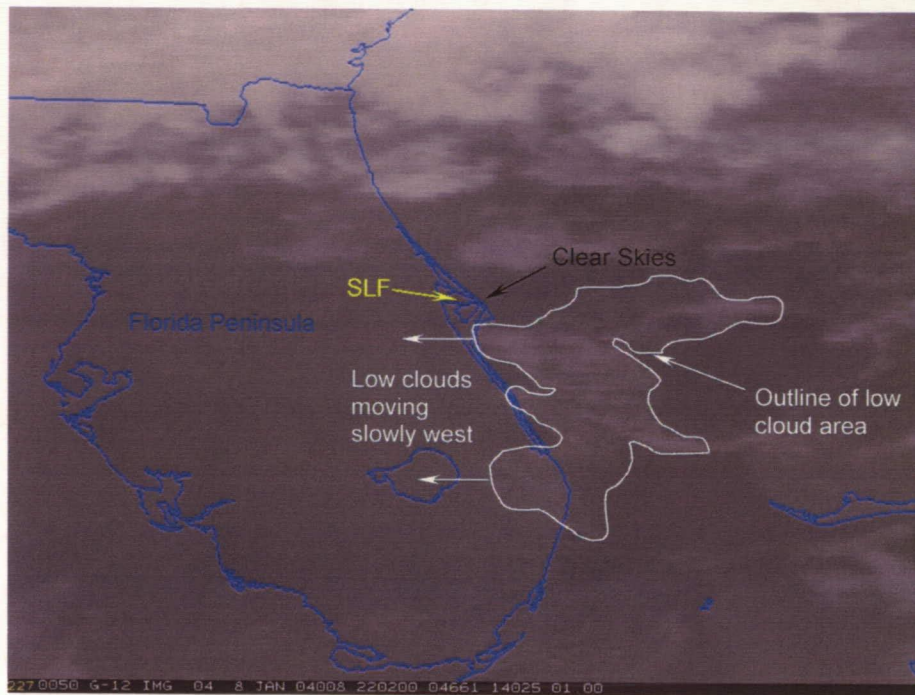


Figure 5. Infrared satellite imagery from 8 January 2004 at 2202 UTC. Clouds existed offshore to the northeast and east-southeast of KSC/CCAFS.

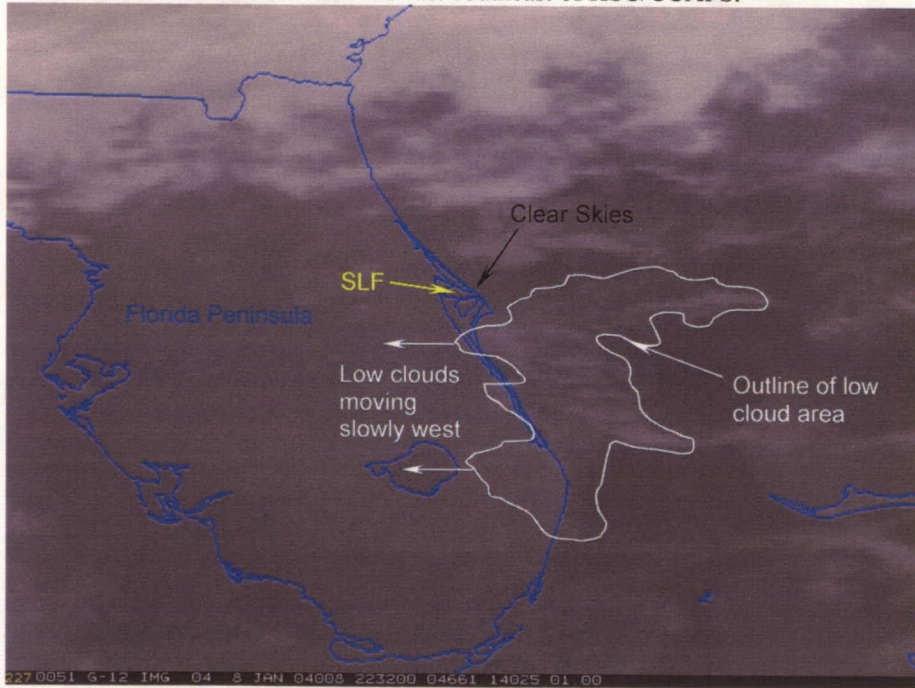


Figure 6. Infrared satellite imagery from 8 January 2004 at 2232 UTC. Clouds were still evident over the ocean northeast and east-southeast of KSC/CCAFS and skies were clear at the SLF.

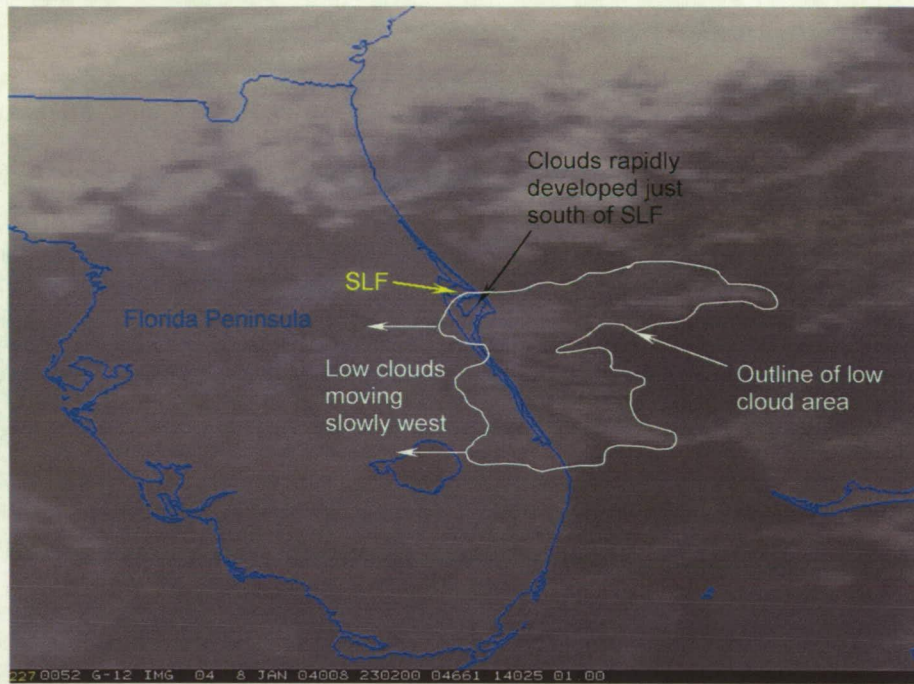


Figure 7. Infrared satellite imagery from 8 January 2004 at 2302 UTC. Low clouds existed over the southern KSC/CCAFS region just south of the SLF.

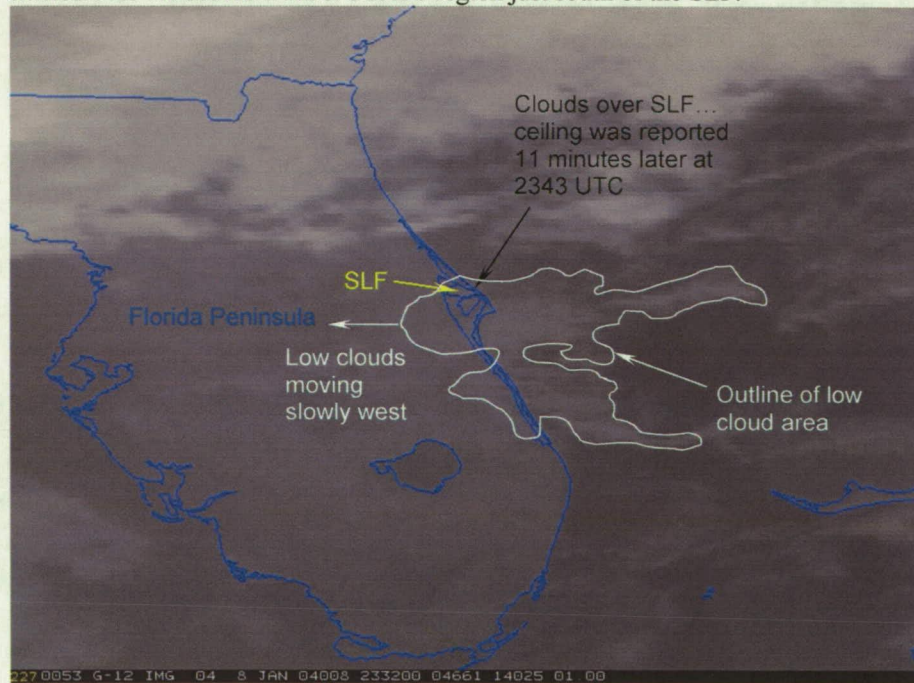


Figure 8. Infrared satellite imagery from 8 January 2004 at 2332 UTC. Clouds were nearly over the SLF.

This case shows the conditions associated with one rapid low ceiling development event during the nighttime hours. Because there were only six such events identified in this dataset, it may not be representative of the conditions required for a majority of nighttime events. The conditions in this case are similar to those prevalent in the daytime events identified in the first phase of this project (Case and Wheeler, 2005). Of the other five rapidly developing cases in this dataset, four had low-level inversions and five had veering winds.

4 Composite Results

This section summarizes the meteorological characteristics of the 6 rapidly developing low ceiling events, and compares/contrasts the meteorological and thermodynamic characteristics between the 6 event and 80 non-event days when low ceilings existed, but either advected into the area or did not form rapidly.

4.1 Summary of Rapid Low Ceiling Development Events

For both phases of this work, a rapid stable low cloud development event was defined as an observed ceiling at or below 8000 ft over the SLF that developed rapidly in place. The POR for this phase was the cool seasons in the years 1994-2005, and the purpose was to determine the weather conditions associated with rapid ceiling development during the nighttime hours between 2200 and 1000 UTC. Potential events with ceilings due to rain or fog were not considered. Potential events without soundings available at both 2200 and 1000 UTC were also not considered. The AMU investigated meteorological characteristics similar to those in Phase I, including the amount of moisture in the boundary layer, and the shear in the vertical wind profile from the surface to 15,000 ft, and the base, top, and strength of any existing inversions.

Unlike the daytime events, only 7% of all nighttime potential low-ceiling events were identified as rapidly-developing events. In contrast, nearly 30% of the 68 potential daytime events were identified as rapid development cases. The other 93% of the nighttime potential events were identified as advection situations. This implies nighttime rapidly developing stable low cloud events do not occur very often, and certainly not as often as the daytime events. A summary of the meteorological characteristics of each nighttime event is given in Table 2. The inversion strengths in Table 2 may be under-estimates of the actual magnitude because the sounding data interpolated to 1000 ft levels were used to obtain the values. In some instances, the inversions may have been less than 1000 ft deep and the interpolated sounding data may have smoothed out the magnitude of the inversions, especially for those based above the surface. Because there were only 6 events, any statistics generated from the data in Table 2 could not be considered robust or significant.

Table 2. Summary of the 6 rapid low ceiling development events and their meteorological characteristics. The mean quantity of RH is given for all levels at and below the inversion, if one existed. The wind direction change with height was determined by examining the sounding data from the surface to 15,000 ft.

Event Date	Onset Time (UTC)	Dissipation Time (UTC)	Highest Inversion Height (ft)	Inversion Strength (°C)	Mean RH (%)	Δ Wind Direction w/Height
01/29/2002	0200	0400	none	-	-	veering
11/12/2002	1038	1400	5000	1.1	92	backing
11/27/2003	0545	0700	none	-	-	veering
01/08/2004	0215	0600	4000	3.7	84	veering
03/11/2005	1100	1600	4000	2.1	89	veering
11/12/2005	1004	1500	6000	2.7	82	veer → back

4.2 Comparison of Characteristics in Event / Non-Event Days

Since all 86 potential events had both low cloud ceilings at TTS and no rain or fog within 3 hours of the ceiling event, one would expect that many meteorological characteristics would be similar between the 6 rapid-development days and the 80 non-development days. Figures 9 through 11 illustrate these common meteorological characteristics between event and nonevent days. Both event and non-event days had wide-ranging values for the highest inversion heights (Figure 9), inversion strength ($\Delta T = T_{\text{top}} - T_{\text{bottom}}$) (Figure 10), and generally had mean RH above 65% below the inversion (Figure 11). No distinguishable differences existed between any of these criteria.

The challenge to the forecaster is discerning whether low cloud ceilings will form when ceilings do not already exist in this type of environment. All of the 80 non-event situations were classified as such after examining the infrared satellite imagery. These non-events had an obvious advection signature, typically off of the Atlantic Ocean, or else had widespread cloud ceilings that would be easier for a forecaster to discern as a "No-Go" condition for a

shuttle landing at the SLF. As stated in Section 1 (Introduction), advection scenarios are not a concern to forecasters since they can monitor the continuity of the low cloud ceilings with sufficient lead-time for landing predictions. The six nighttime events analyzed for this report typically experienced rapid cloud formation within 30 minutes or less, with no prior extensive cloud decks present over east-central Florida and are the most challenging ceiling forecasts to make.

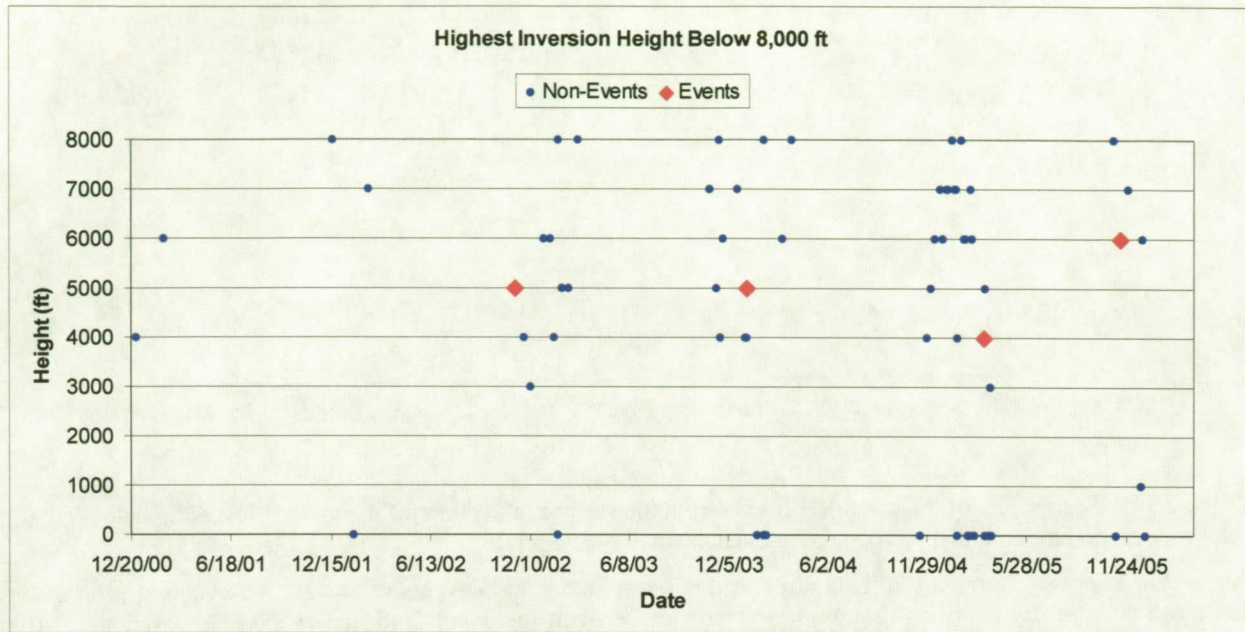


Figure 9. Scatter plot of the base of the highest inversions below 8000 ft (in ft) during events (large red diamond) and non-events (small blue circle).

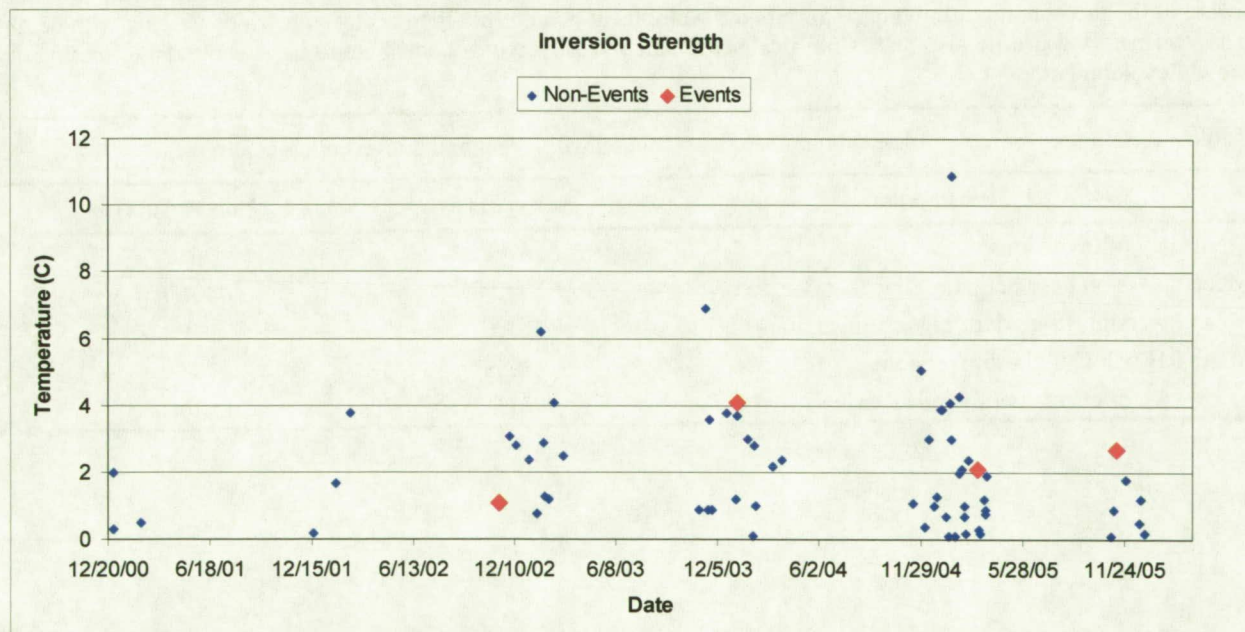


Figure 10. Scatter plot of the inversion strength ($\Delta T = T_{\text{top}} - T_{\text{bottom}}$, in $^{\circ}\text{C}$) of the highest inversion below 8000 ft during events (large red diamond) and non-events (small blue circle).

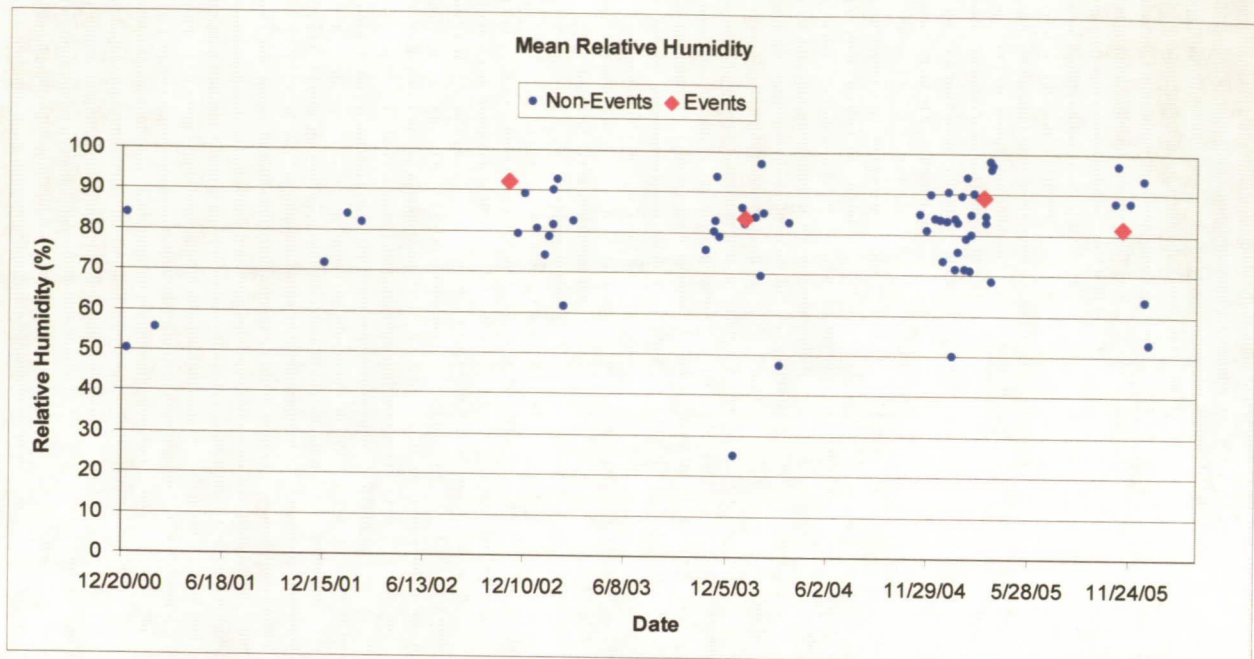


Figure 11. Scatter plot of the mean RH (in %) from the surface to the base of the highest inversion below 8000 ft during events (large red diamond) and non-events (small blue circle).

Table 3 shows a summary of meteorological parameters for the 6 events versus 80 non-events. Unfortunately, there are no significant distinguishable characteristics between the events and non-events. However, the vertical wind profile from the surface to 15,000 ft indicates a veering wind profile 83% of the time for events and 61% of the time for non-events. Such a profile represents a warm advection pattern that favors rising motion, and thus, cloud formation in a moist environment. Therefore, when a clear advection event is not in progress, a forecaster should be aware of the fact that nighttime rapid low cloud development is more likely to occur with winds veering with height. The veering wind profile also makes physical sense since veering winds contribute to large-scale rising motion and cloud development.

Table 3. Summary of meteorological parameters associated with event and non-event cases.

Parameter	Events	Non Events
Frequency of inversions	67%	76%
Mean inversion base height of highest inversion	5000 ft	4400 ft
Mean inversion strength of highest inversion	2.5°C	2.1°C
Mean RH below highest inversion	87%	79%
Frequency of events with winds veering with height	83%	61%

5 Summary and Conclusions

This report describes the AMU work in developing a database of potential nighttime events that experienced rapid low cloud formation in a stable atmosphere, resulting in ceilings below 8000 ft at the SLF. The report also documents the meteorological conditions associated with the nighttime rapid low ceiling formation. Meteorological parameters were summarized for 6 nighttime events with rapid low cloud ceiling formation and 80 nighttime non-events consisting of advection or widespread low cloud ceilings.

There were no discerning differences between the meteorological conditions for both the events and non-events. With only six cases in which a ceiling developed rapidly in place, meaningful statistics could not be calculated. When a rapid development occurred, the average RH below the inversions was 87% while non-events had an average RH of 79%. One key parameter appears to be the vertical wind profile in the XMR sounding. Eighty-three percent of the rapid development events had veering winds with height below 15,000 ft while 61% of the non-events had veering winds with height. Veering winds indicate a warm-advection regime, which supports large-scale rising motion and ultimately cloud formation in a moist environment.

Since there were only 6 rapid development events out of 86 total cases (7%), it is likely that rapid low cloud development is not a common occurrence during the night, or at least not as common as during the day. In the AMU work on the daytime rapid low cloud development (Case and Wheeler 2005), nearly 30% of the low cloud ceiling cases investigated were identified as rapidly developing events.

Future work could include a cloud-development climatology for both nighttime and daytime hours in the cool season. This would give the forecasters an indication of the frequency of low cloud ceilings due to cloud advection or sudden cloud development, surface fronts, precipitation, fog, etc.

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List of Acronyms

Term	Description
AMU	Applied Meteorology Unit
CCAFS	Cape Canaveral Air Force Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
NOR	White Sands Space Harbor, NM station identifier
RH	Relative Humidity
SLF	Shuttle Landing Facility
SMG	Spaceflight Meteorology Group
TTS	SLF 3-letter identifier
XMR	CCAFS radiosonde 3-letter identifier

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