NASA Contractor Report CR-2006-214193

Analysis of Rapidly Developing Low Cloud Ceilings in a Stable Environment

Prepared By:
The Applied Meteorology Unit

Prepared for:
Kennedy Space Center
Under Contract NAS10-01052

NASA
National Aeronautics and
Space Administration

Office of Management
Scientific and Technical
Information Program

2006

Attributes and Acknowledgments

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Executive Summary

This report describes the work done by the Applied Meteorology Unit (AMU) in developing a database of days 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). The meteorological conditions favoring the rapid formation of low ceilings include the presence of any inversion below 8000 ft, high relative humidity 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 days with rapid low ceiling formation and days with low ceilings resulting from other mechanisms. The AMU found that the vertical wind profile is the probable discerning factor between the rapidly-forming ceiling days and other low ceiling days at TTS. Most rapidly-developing low ceiling days had a clockwise turning of the winds with height, whereas other low ceiling days typically had a counter-clockwise turning of the winds with height or negligible vertical wind shear.

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 1993–2003 for days 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 morning Cape Canaveral, FL rawinsonde (XMR) 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. Days with precipitation or noticeable fog burn-off situations were excluded from the database. Only the daytime hours were examined for possible ceiling development events since low clouds are easier to diagnose with visible satellite imagery. Follow-on work could expand the database to include nighttime cases, using a special enhancement of the infrared imagery for identifying areas of low clouds.

The report presents two sample cases of rapidly-developing low cloud ceilings. These cases depict the representative meteorological and thermodynamic characteristics of such events. The cases also illustrate how quickly the cloud decks can develop, sometimes forming in 30 minutes or less.

The report also summarizes the composite meteorological conditions for 20 event days with rapid low cloud ceiling formation and 48 non-events days consisting of advection or widespread low cloud ceilings. The meteorological conditions were quite similar for both the event and non-event days, since both types of days experienced low cloud ceilings. Both types of days had a relatively moist environment beneath an inversion based below 8000 ft. In the 20 events identified, the onset of low ceilings occurred between 1200–1800 UTC in every instance.

The distinguishing factor between the event and non-event days appears 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 whereas 83% of the non-events had a counter-clockwise turning of the winds with height or negligible vertical wind shear. A clockwise turning of the winds with height indicates a warm-advection regime, which supports large-scale rising motion and possible cloud formation. Meanwhile, a counter-clockwise turning of the winds with height indicates cold advection or sinking motion in a post-cold frontal environment.

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1 Introduction

1.1 Motivation

Forecasters at the Space Meteorology Group (SMG) issue 30 to 90 minute forecasts for low cloud ceilings at the Shuttle Landing Facility (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. The Applied Meteorology Unit (AMU) was tasked to examine archived events of rapid stable cloud formation resulting in cloud ceilings below 8000 ft, and document the atmospheric regimes favoring this type of cloud development. The AMU was asked to distinguish between cloud advection and development cases, since SMG forecasters can already accurately predict low ceilings in advection situations.

1.2 Background/Objective

SMG forecasters have responsibility for issuing Shuttle landing forecasts for standard and abort landing scenarios. These landing scenarios include Return to Launch Site (RTLS) abort landings at KSC, abort-once-around at the primary landing site, and standard End Of Mission (EOM) at the Kennedy Space Center (KSC), Edwards Air Force Base, CA (EDW), and/or White Sands Space Harbor, NM (NOR; Brody et al. 1997).

A variety of Space Shuttle Flight Rules (FR) apply for all of these landing scenarios at each site involving cloud ceiling heights, visibility, cross/head/tail wind speeds, precipitation, etc. (NASA/JSC 2004). This report focuses only on the cloud ceiling rule as applied to the KSC landing site (Table 1). The most commonly encountered cloud ceiling height restriction for shuttle missions is 8000 ft, which is the focus of this study.

Previous work by the AMU has involved the development of observations-based statistical equations for short-term prediction of low ceilings at TTS (Lambert 2001). This work can offer a first-guess for predicting low ceiling occurrence during any time of the year. This study, however, focuses on ceiling development under specific meteorological conditions that occur during the winter months.

Table 1. Space Shuttle Flight Rules for cloud ceiling heights and visibility restrictions pertaining to various landing scenarios and locations (NASA/JSC 2004).

<table>
<tr><th colspan="3">Ceiling / Visibility
(kft)/(sm)</th><th>Redundant Microwave Landing System (MLS)</th><th>Single-String MLS</th><th>No MLS</th></tr>
<tr><td rowspan="4">KSC, EDW, NOR, Abort Once Around, Daily Primary Landing Site (PLS) Selection (all sites)</td><td rowspan="2">Concrete</td><td>Day</td><td rowspan="4">≥8/5
(Wx RECON Required)</td><td colspan="2">≥10/7</td></tr>
<tr><td>Night</td><td colspan="2">NO-GO</td></tr>
<tr><td rowspan="2">Lakebed</td><td>Day</td><td></td><td>≥10/7</td></tr>
<tr><td>Night</td><td>≥15/7</td><td>NO-GO</td></tr>
<tr><td rowspan="2">Return To Launch Site (RTLS),
Trans-oceanic Abort Landing (TAL)</td><td rowspan="2">Concrete</td><td>Day</td><td rowspan="2">≥5/4 RTLS
≥5/5 TAL
(Wx RECON Required)</td><td colspan="2">≥10/7</td></tr>
<tr><td>Night</td><td colspan="2">NO-GO</td></tr>
<tr><td colspan="3">Augmented Contingency Landing Site /
East Coast Abort Landing /
Emergency Landing Site</td><td colspan="2">0/0</td><td>≥8/5</td></tr>
<tr><td colspan="3">Predeorbit:
One Auxiliary Power Unit (APU) failed OR
Attempt two APU's procedure</td><td colspan="3">≥10/7</td></tr>
</table>

The objective of this report is to identify and examine days with rapidly developing cloud ceilings below 8000 ft. These events must occur in an environment characterized by a stable, “capped” thermodynamic profile. The overall goal is to

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

This report is organized as follows. Section 2 describes the objective and subjective methodology used to identify days with rapid, stable cloud development. Section 3 provides an analysis of two samples of rapidly-forming low ceiling events. Section 4 presents the composite atmospheric characteristics that favor stable cloud formation, and Sections 5 and 0 provide a summary and references, respectively.

2 Methodology

The forecasters at SMG indicated that these events often take place in the cool season (November to March) during daylight hours. Also, daytime events are much easier to identify with visible satellite imagery, since developing low, warm clouds can be more challenging to identify in infrared imagery. Therefore, the AMU collected data from the morning Cape Canaveral Air Force Station (CCAFS) rawinsonde (XMR) and hourly surface observations at TTS between 1100–2300 UTC during the cool season months of November to March 1993–2003, for a total of 10 cool seasons. Three additional cases identified by SMG were added from 2004 and 2005. Due to the labor intensive process of acquiring and restoring satellite imagery, the analysis was limited to these 10 cool seasons in this study.

Due to the large number of cool-season days to examine for stable low-cloud formation, the AMU devised an objective method to sift through all data and retain only days with an inversion below 8000 ft at XMR and observed cloud ceilings below 8000 ft at TTS. By eliminating all days without low-level inversions and low cloud ceilings, this method helped to narrow down the potential case days.

2.1 Identify Low-Level Inversions

Archived sounding data were obtained from Computer Sciences Raytheon for the months and years listed above. The AMU then developed software to identify all inversions below 8000 ft with at least a 1°C increase in temperature over any depth. For days that had a low-level inversion at least 1°C in strength, the software would output the base, depth, and magnitude of the inversion for the sounding nearest in time to 1200 UTC. Also, the program would output data every 1000 ft beginning at the surface up to 8000 ft and included altitude, pressure, wind direction, wind speed, temperature, dew point, relative humidity, and the cumulative mean wind direction and speed. These parameters were used to help narrow down the number of potential days meeting the pre-defined criteria for the task, as well as provide output for assessing potential rapid low-cloud development events. If more than one inversion was present in the morning sounding, then the characteristics for the highest inversion were recorded in order to focus on the inversions acting to "cap" the lower atmosphere.

2.2 Identify Low Cloud Ceilings

The AMU obtained archived surface observations from the Air Force Combat Climatology Center (AFCCC) for all central Florida surface reporting sites (Table 2**,** Figure 1) for the period of record, and then developed additional software to read in the AFCCC-formatted data, and parse out the pertinent cloud information from the archived METAR reports. The TTS data were processed first in order to obtain a record of cool-season days with low cloud ceilings that would impact the cloud ceiling height FR for Shuttle landings at KSC.

The program was designed to output any reports of cloud ceilings and their accompanying height below 8000 ft between the hours of 0600 and 2300 UTC. The output included a summary of the total number of hourly reports for each sky condition (clear, scattered, broken, overcast, and missing). In addition to cloud ceilings, the program also output any hourly observation of precipitation and/or fog to distinguish the rapidly-developing low cloud ceilings from those associated with fog burn-off and/or precipitation.

The days with both low-level inversions and low cloud ceilings at TTS were then combined into a common Microsoft Excel spreadsheet for further examination. Data from several nearby central Florida METAR stations (Table 2) were then processed to compare the onset times of low cloud ceilings with the onset times at TTS. Examining the cloud ceiling observations at METAR stations near TTS helped distinguish between days with low cloud ceiling formation and those with advection of low clouds. The onset time of cloud ceilings should be nearly concurrent at nearby METAR sites in the rapid-development situation, whereas with advection, the cloud ceiling onset times should indicate a temporal trend between stations.

Table 2. List of the central Florida surface station data used for identifying cloud ceilings below 8000 ft.

Station Name	Station ID
Shuttle Landing Facility	TTS
Titusville	TIX
Sanford	SFB
Orlando Regional Airport	ORL
Orlando International Airport	MCO
Ocala Municipal Airport	OCF
Melbourne	MLB
Leesburg	LEE
Kissimmee	ISM
Winter Haven	GIF
Daytona Beach	DAB
Patrick Air Force Base	COF
Bartow Municipal Airport	BOW
The Villages	VVG
Vero Beach	VRB

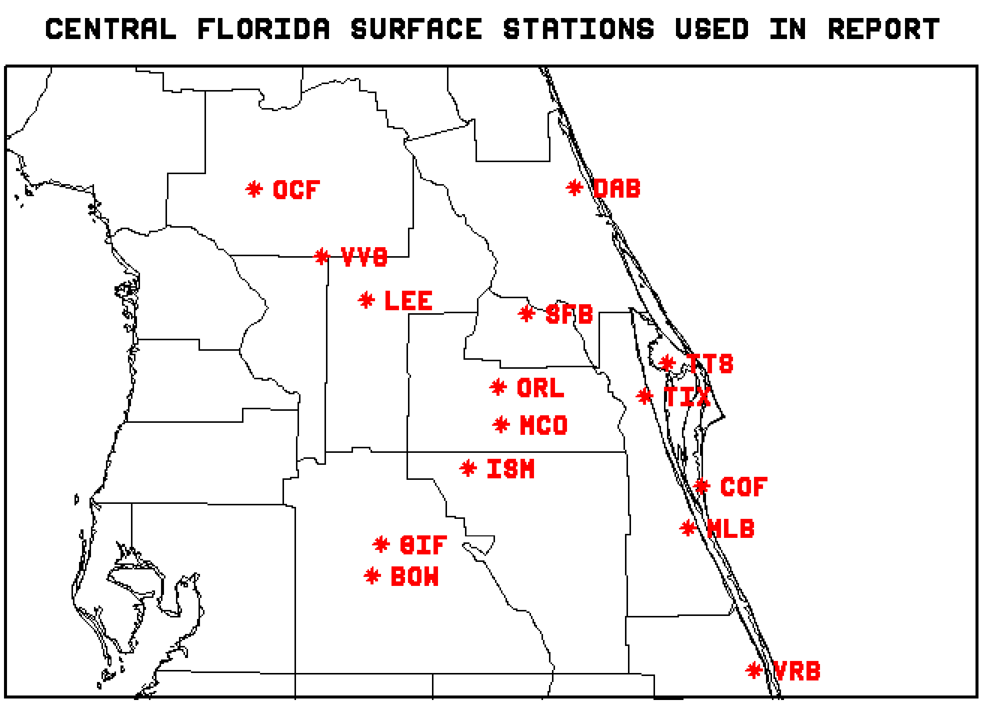

Figure 1. A map showing the central Florida surface reporting stations used to determine rapidly-developing low ceiling events from the 10-year period of record.

2.3 Develop Database of Possible Events

The AMU then conducted a subjective analysis of the output from the programs just discussed in order to identify potential case days. Through this subjective analysis, the database was narrowed further to exclude precipitation events, days with ceilings resulting from early morning fog, and days with ceilings below 8000 ft all day, since the goal of the task is to study the ceiling formation. Days were identified as potential events if they exhibited each of the following three elements:

- A low-level inversion,
- High relative humidity near and below the inversion, and
- A ceiling below 8000 ft.

All potential low-cloud formation days were entered into an Excel spreadsheet for record-keeping. At this point in the analysis, there were 68 days identified as possible rapid low-cloud development events.

2.4 Examine Visible Satellite Imagery

The next step after identifying the possible events was to obtain visible satellite imagery for the remaining days to confirm whether the day had rapid cloud development, advection, or some combination of both. The only way to confirm that a day had cloud development rather than advection was to examine the satellite imagery.

The AMU restored satellite imagery already archived in recent years. For the remaining days, satellite imagery was purchased from the Man computer Interactive Data Access System (McIDAS) Users Group at the University of Wisconsin. All imagery was viewed with the McIDAS software and the AMU wrote a script to save JPEG files of each satellite image for easy future reference. Finally, after examining satellite imagery for all 68 possible events, there were 20 confirmed rapid low-cloud formation events, 3 of which were recent events identified by SMG. There may be several more events from the study's period of record that were not identified by this technique; however, this method provided the most efficient way to identify events given the available resources for this task.

3 Individual Case Study Analysis

This section presents two examples of rapidly-developing low ceilings, from 6 January 1995 and 30 January 1999. These days exhibited similar synoptic and thermodynamic conditions as highlighted below.

3.1 Event Day 1/6/1995

3.1.1 Weather Discussion

The weather pattern over Florida on 6 January 1995 was controlled by a high pressure system located along the U.S. East Coast (Figure 2). This air mass resulted in a stable atmosphere and a light wind out of the east-southeast in central Florida. There was a north-south thermal gradient as indicated by a surface temperature of 51ºF in Orlando and 37ºF at Jacksonville. A frontal system had passed through the area the day before and was located in the Florida straits. Notice the weak warm/moist advection occurring across southern and central Florida in Figure 2.

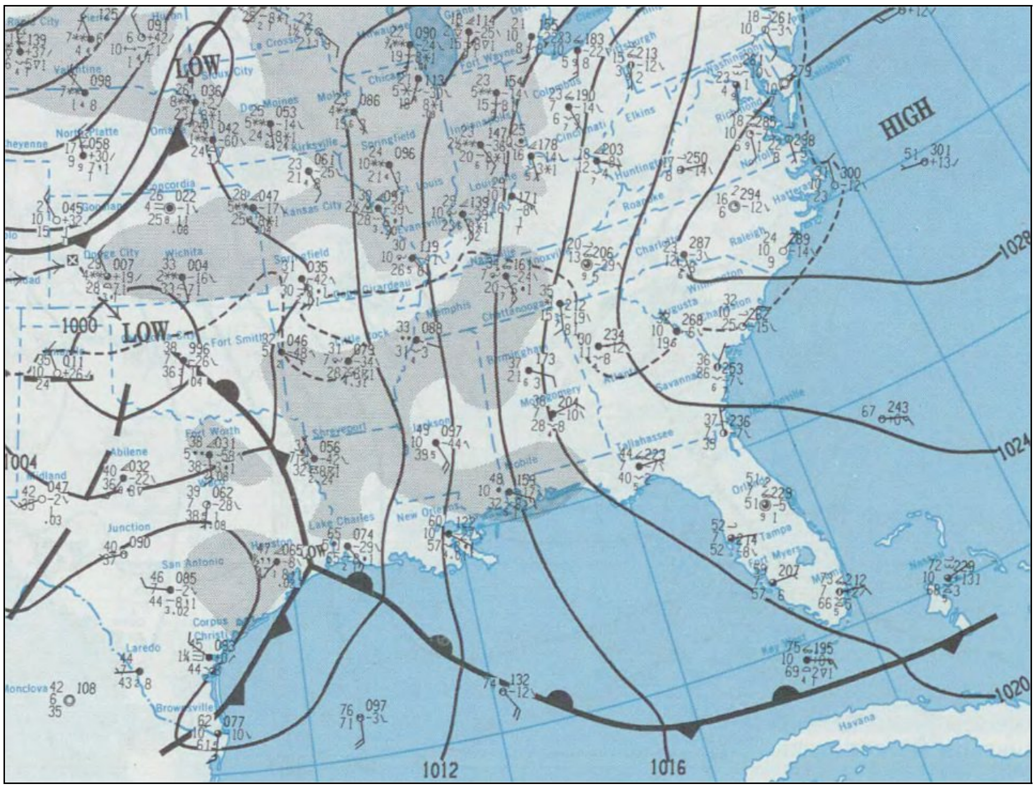

Figure 2. Surface analysis at 1200 UTC 6 January 1995.

3.1.2 Analysis of Data

The morning rawinsonde for XMR contained several inversions (Figure 3). The first was at the surface due to the radiational cooling that had taken place overnight. A possible frontal inversion was located between 900 and 800 mb and a subsidence inversion was found between 740–700 mb. Winds just above the surface inversion were southeasterly at 5 kts veering to southwesterly up to 850 mb. Relatively high moisture was trapped below the 900-mb inversion. The magnitude of the 900-mb inversion was 2.2º C and the average layer relative humidity was 85%.

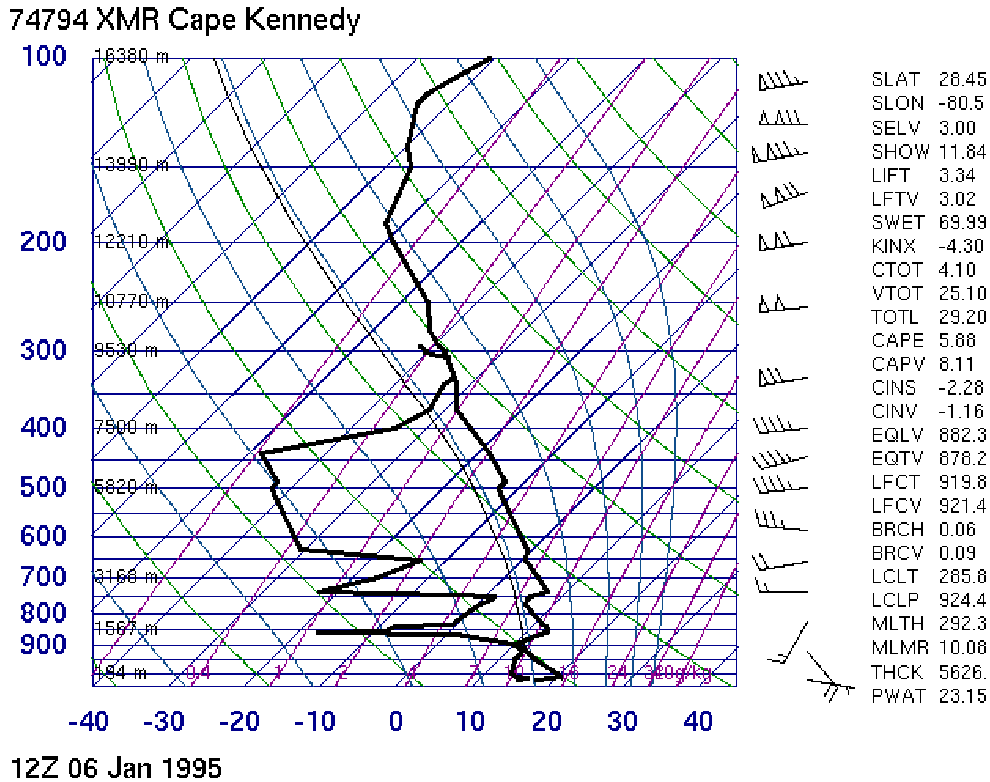

Figure 3. XMR rawinsonde at 1200 UTC 6 January 1995. Note the strong inversion near 900 mb, veering winds with height, and the high relative humidity beneath the inversion.

Visible satellite imagery was analyzed during the hours of 1100 to 2200 UTC. The first image at 1245 UTC (Figure 4) shows high clouds over central Florida with little indication of low-level clouds. By 1345 UTC (Figure 5) the high clouds had thinned over east-central Florida, and very little low cloud cover occurred through 1615 UTC (Figure 6). From 1645 UTC (Figure 7) to 1715 UTC (Figure 8) low clouds began forming just west of CCAFS over mainland Florida. This area then expanded over the CCAFS and KSC areas by 1745 UTC (Figure 9).

A hypothetical 90-minute Space Shuttle EOM forecast issued on or just before 1615 UTC may have called for "Go" conditions based on the prevailing cloud trends in this example. However, within 90 minutes, cloud ceilings developed over KSC/CCAFS, which would have resulted in an observed "No-Go" condition at the time of landing. Once the de-orbit burn occurs 90 minutes prior to landing, the orbiter is committed to land at that particular site. Therefore, 90-minute EOM forecasts must reflect a high degree of forecaster confidence since there is very little margin of safety built into the ceiling flight rules. Scenarios as the one described here need to be understood and recognized as a potential threat to the safety of flight.

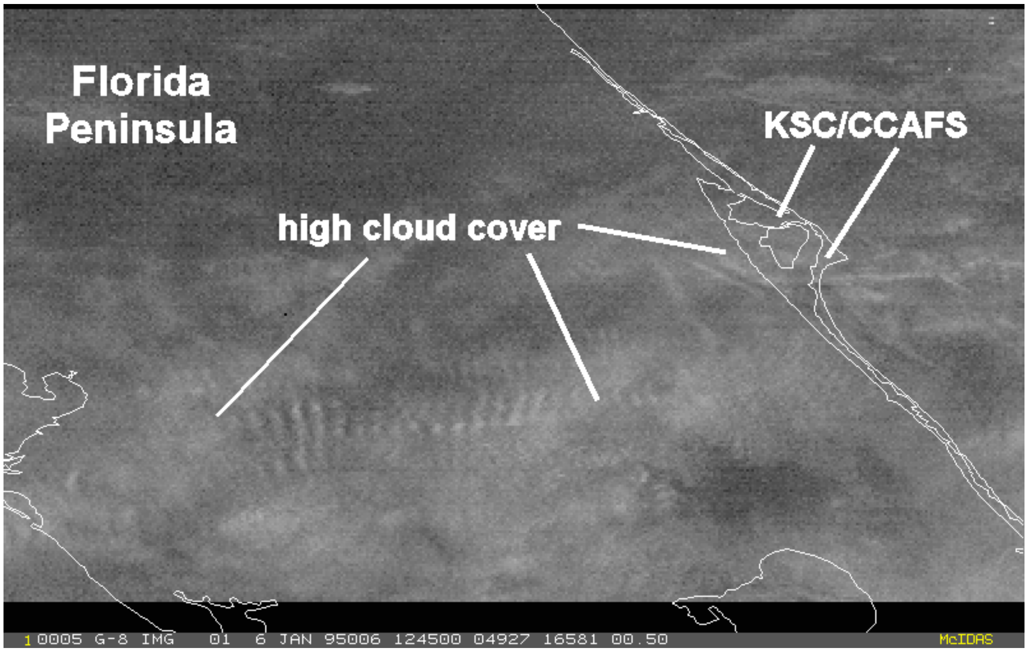

Figure 4. Visible satellite image on 6 Jan 1995 at 1245 UTC, with high clouds over central Florida.

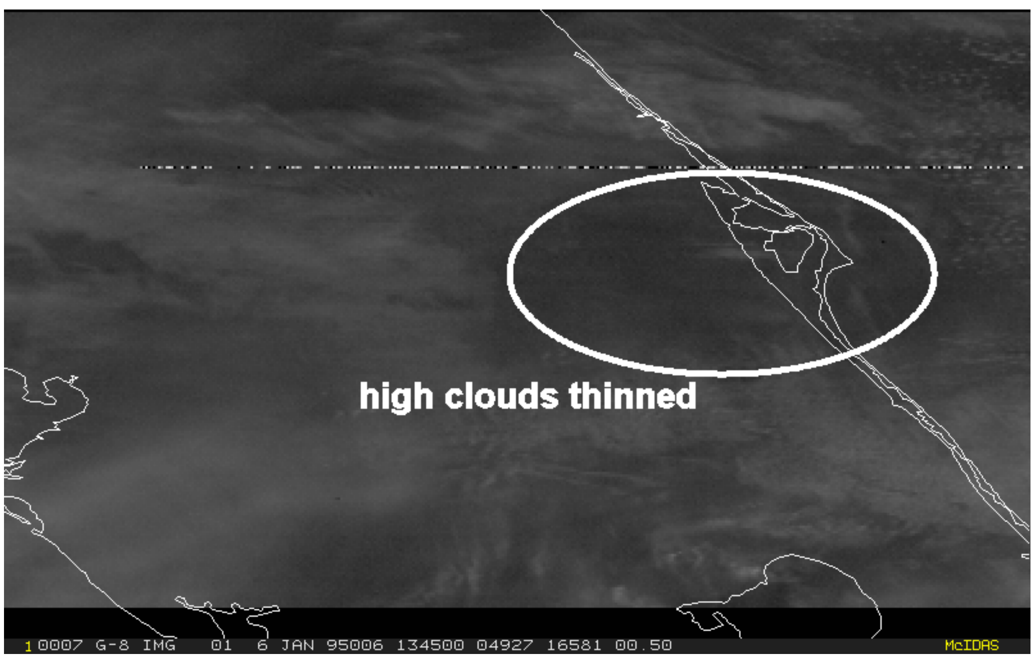

Figure 5. Visible satellite image at 1345 UTC on 6 Jan 1995. By this time the high clouds have thinned near CCAFS.

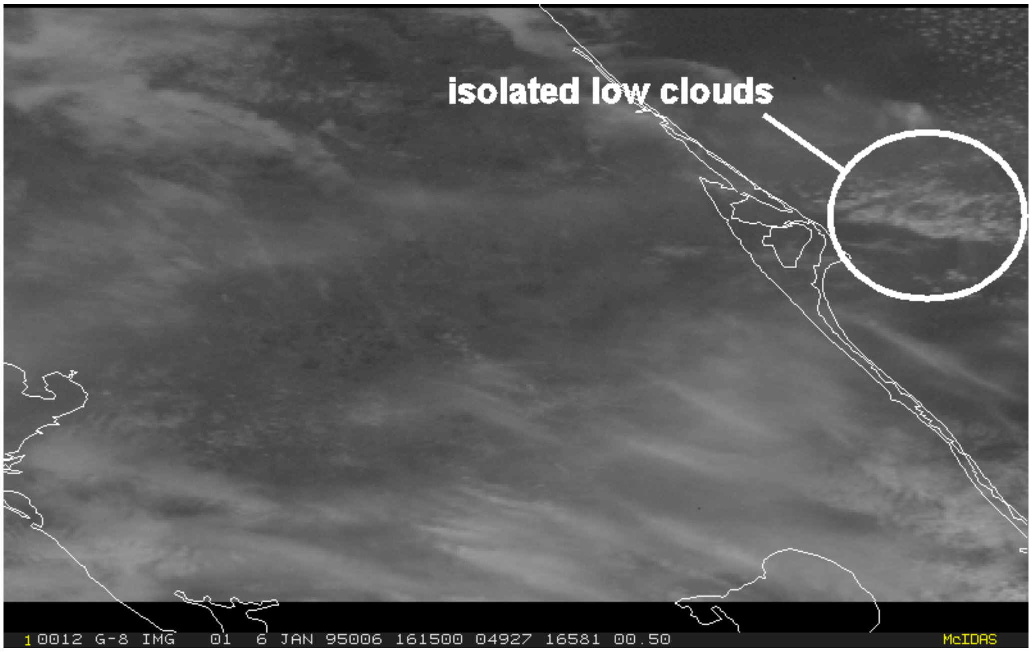

Figure 6. **Visible satellite image at 1615 UTC on 6 January 1995, with no signs of low clouds over east-central Florida.**

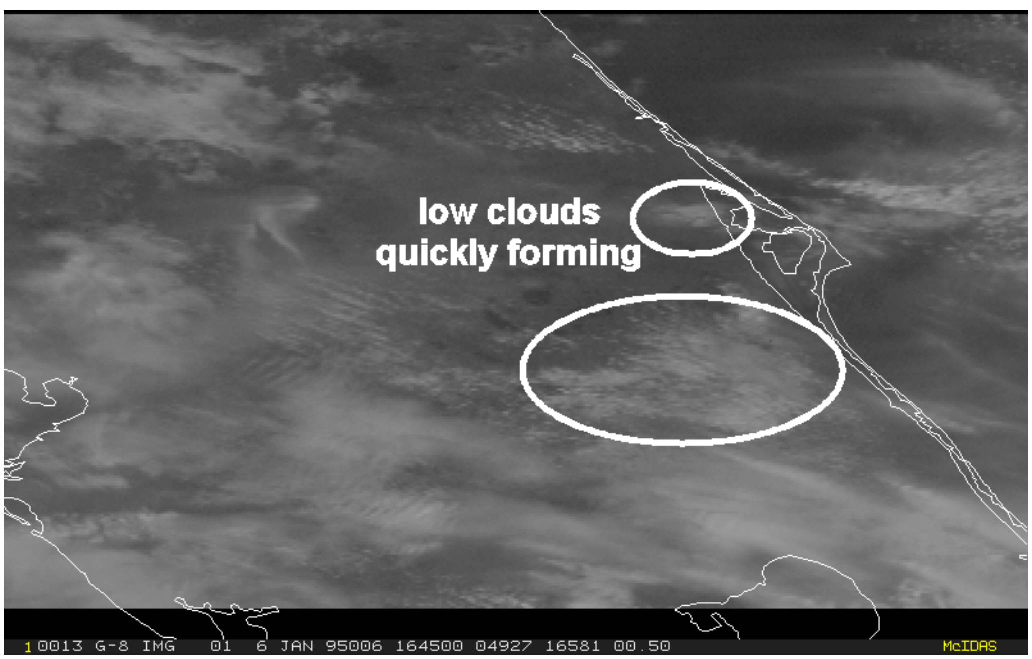

Figure 7. **Visible satellite image at 1645 UTC on 6 January 1995, with some low clouds beginning to rapidly form south and west of KSC/CCAFS.**

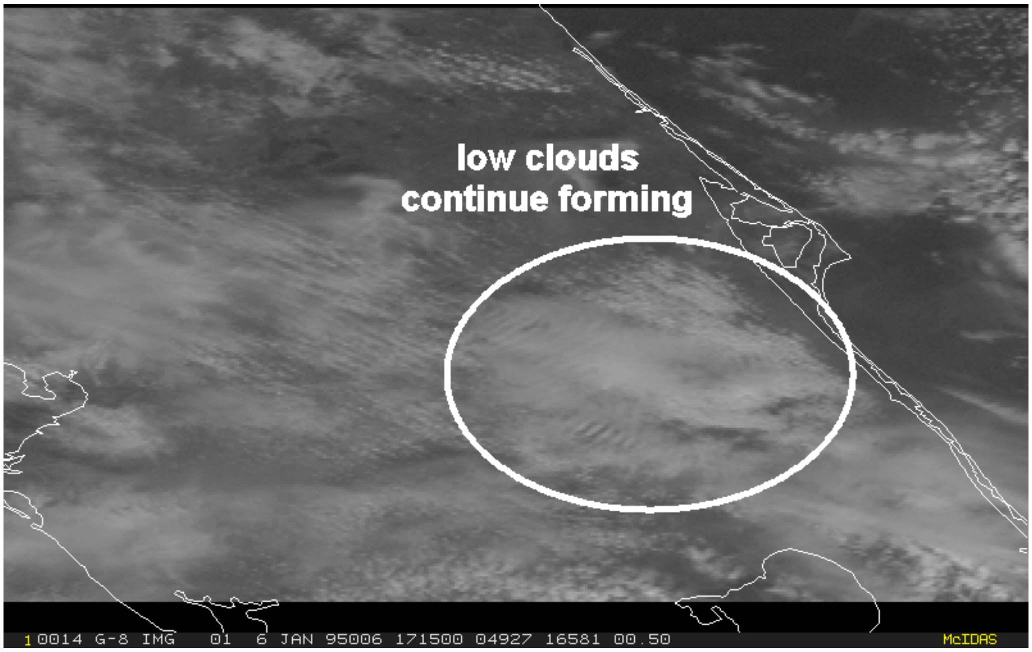

Figure 8. Visible satellite image at 1715 UTC on 6 Jan 1995. Rapid low cloud development is occurring to the west of KSC/CCAFS.

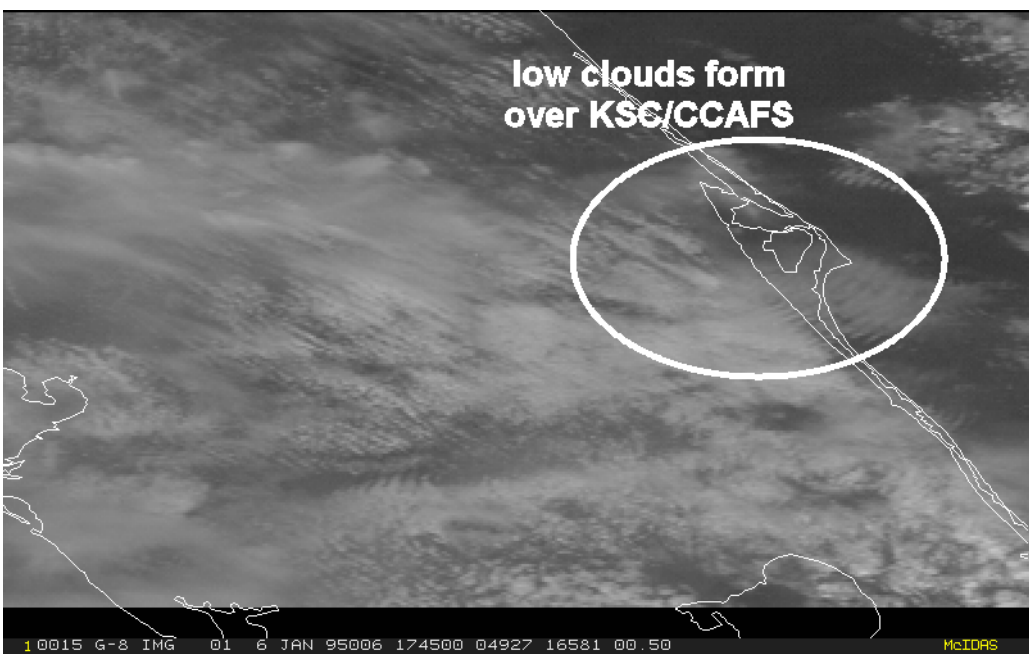

Figure 9. Visible satellite image at 1745 UTC on 6 Jan 1995. Rapid low cloud development is observed over and to the west of KSC/CCAFS.

3.2 Event Day 1/30/1999

3.2.1 Weather Discussion

The weather in Florida was controlled by a weak high pressure ridge on 30 January 1999. There was also a weak stationary frontal boundary extending westward from the Atlantic to Jacksonville, FL, and to a low pressure center near the Oklahoma / Arkansas border (Figure 10). This pattern resulted in a stable atmosphere across central Florida with a light wind out of the east near KSC/CCAFS. Surface temperatures were in the lower 60's across central Florida. As in the previous case, weak warm/moist advection was again prevalent across the Florida peninsula.

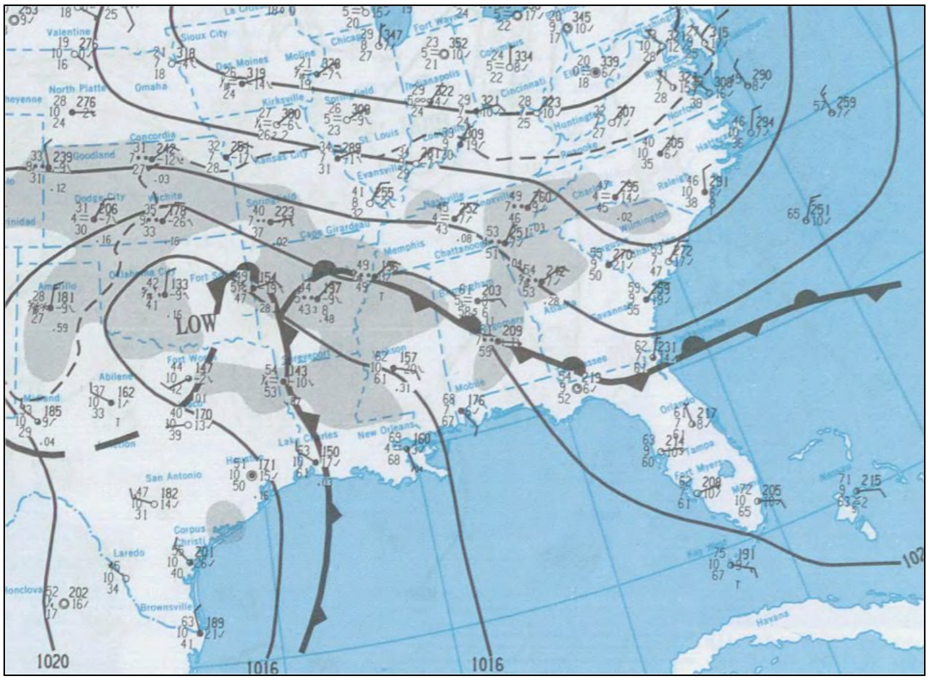

Figure 10. Surface analysis at 1200 UTC on 30 January 1999.

3.2.2 Analysis of Data

The morning rawinsonde for XMR had two inversions present (Figure 11). The first was at the surface due to the radiational cooling that had taken place overnight. A subsidence inversion was located between 800 and 770 mb. Winds just above the surface inversion were southeasterly at 15 kts veering to the southwest up to 700 mb. Moisture was trapped between the surface and the 800-mb inversion. The magnitude of the inversion at 800 mb was 6ºC and the average layer relative humidity beneath the inversion was 72%.

Compare this profile to the XMR sounding on 8 March 1999, a day that also had low ceilings (Figure 12). The ceilings on this day, however, advected from the northeast off of the Atlantic Ocean rather than developed in place. The thermodynamic profiles look quite similar as both days exhibited a strong capping inversion above a relatively moist boundary layer. The main difference lies in the vertical wind profile, as winds veered on the 30 January event while the winds backed on the 8 March non-event. The implications of the vertical wind profile will be addressed in Section 4.

At 1245 UTC, very few clouds were observed over central Florida while scattered areas of low clouds were found to the south and west (Figure 13). Thirty minutes later, scattered clouds began forming over KSC/CCAFS but coverage was not sufficient to cause ceilings (Figure 14). However, by 1345 UTC, low clouds and subsequent ceilings had rapidly developed over the KSC/CCAFS area and adjacent coastal waters (Figure 15).

Once again, a hypothetical 90-minute Space Shuttle EOM forecast issued on or just before 1300 UTC may have called for "Go" conditions based on the prevailing cloud cover. But the rapid low cloud development would have resulted in an observed "No-Go" condition at the hypothetical time of landing, and thus a potential threat to the safety of flight.

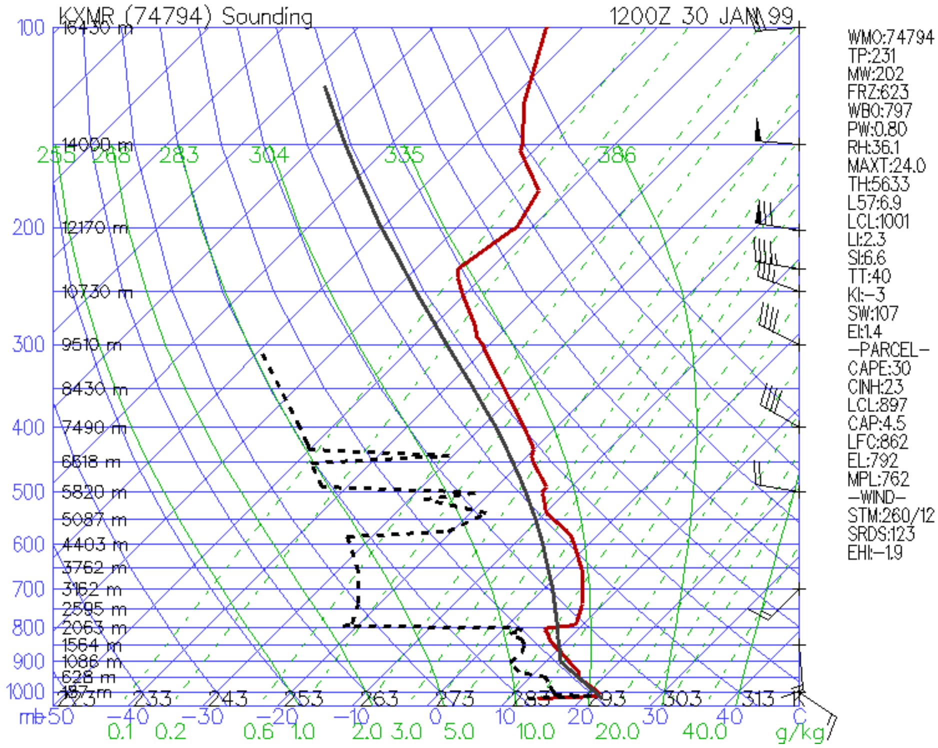

Figure 11. XMR rawinsonde on 30 Jan 1999 at 1200 UTC. Note the strong inversion near 800 mb with fairly high low-level moisture and veering winds from the surface up to 500 mb.

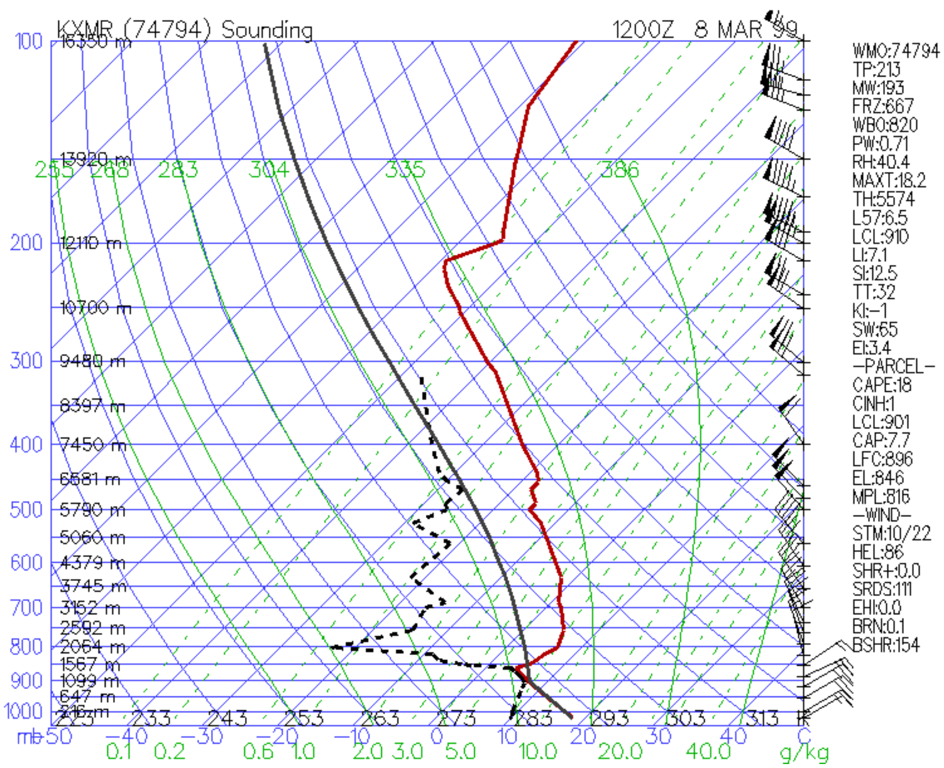

Figure 12. XMR rawinsonde at 1200 UTC 8 Mar 1999. Note the fairly high moisture beneath the inversion near 850 mb, and backing winds from the surface up to 500 mb.

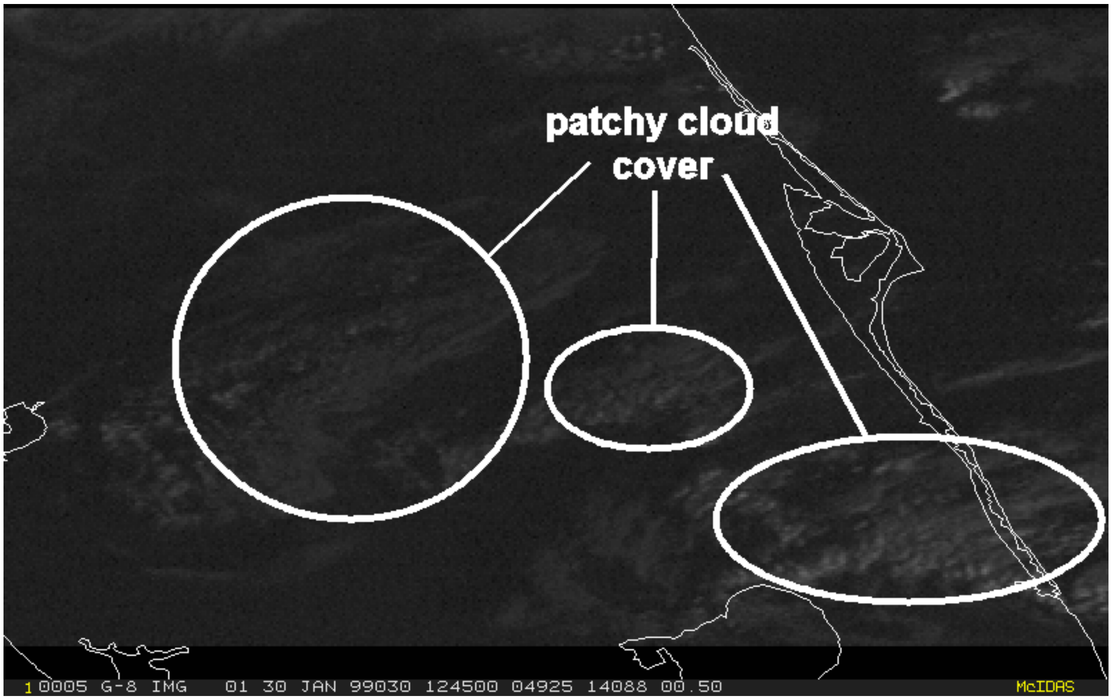

Figure 13. Visible satellite image on 30 Jan 1999 at 1245 UTC. Very scattered low clouds were observed across east-central Florida.

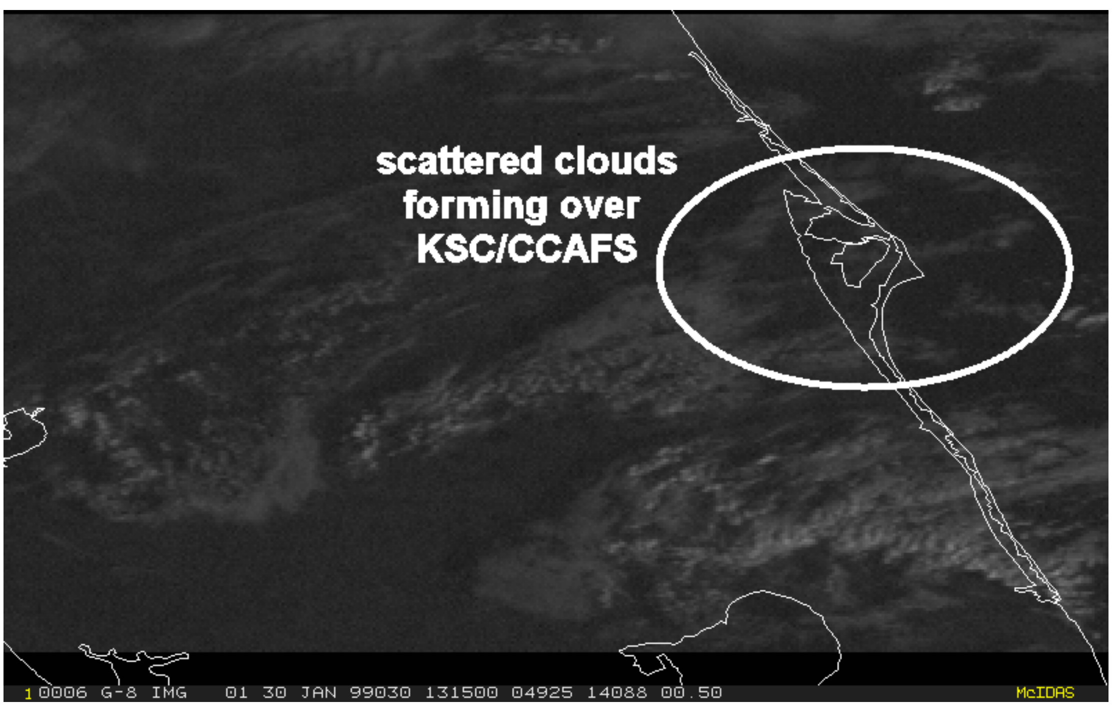

Figure 14. Visible satellite image on 30 Jan 1999 at 1315 UTC. Low clouds were beginning to form across KSC/CCAFS.

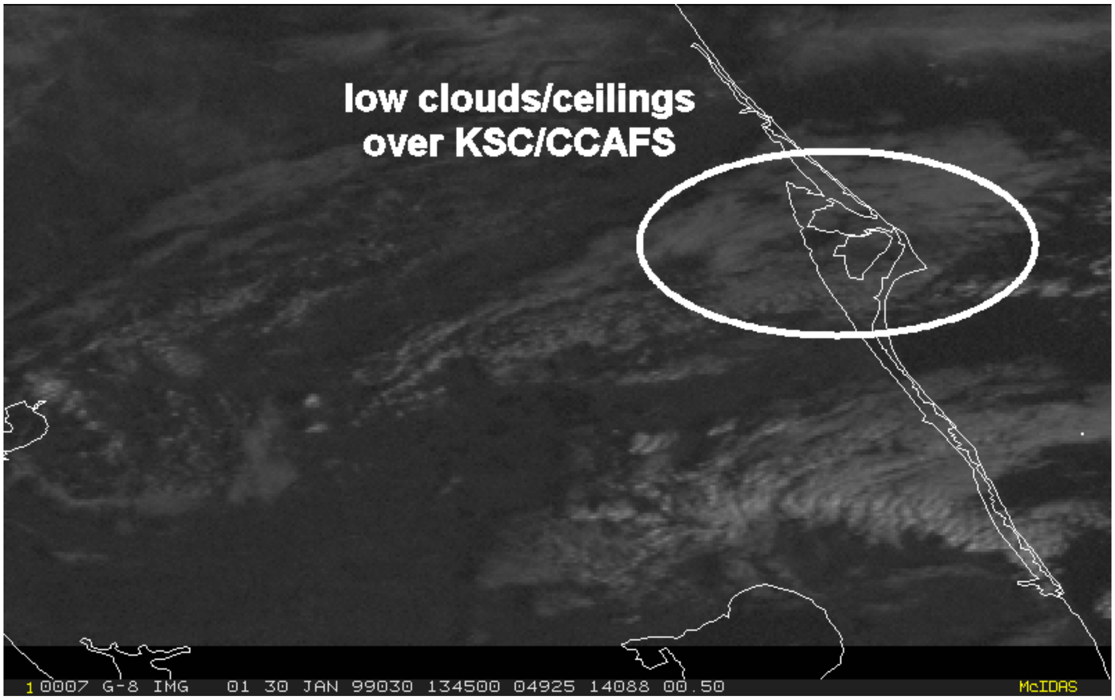

Figure 15. Visible Satellite image at 1345 UTC on 30 Jan 1999. By this time, rapid development of low clouds is observed over CCAFS and adjacent coastal waters.

3.3 Summary of Events

These two cases show the representative conditions associated with rapid low ceiling development days. The development often occurs in 15 to 30 minutes and within a few hours of sunrise, at least with the daytime events examined in this task. The next section summarizes the composite results of all daytime rapidly developing low ceiling events identified by the AMU, and compares/contrasts the meteorological and thermodynamic conditions of event days to non-event days when low ceilings existed, but did not rapidly form.

4 Composite Results

Based on the 68 days flagged as possible stable low-cloud formation days, 20 of the days were confirmed to have rapid development. The remaining 48 days consisted of either advection of low cloud ceilings or widespread cloud ceilings that persisted for much of the day. This section presents the meteorological characteristics of the 20 rapid, stable low cloud development days, and compares the characteristics between the 20 event and 48 non-event days.

4.1 Summary of Rapid Cloud Development Events

By definition, the rapid, stable low ceiling development days consisted of a stable low-level sounding with an inversion present below 8000 ft. The onset/formation times for all events occurred between 1200–1800 UTC, indicating that heating and mixing after sunrise probably helped to trigger the initial low ceiling development. Other event characteristics included a relatively moist mean boundary layer and a veering vertical wind profile from the surface to the middle troposphere. Also, the mean wind flow beneath the inversion tended to have a southerly and/or easterly component, but varied quite substantially from case to case. The dissipation times varied substantially, anywhere from 0.5 hours to 3 hours or more after the initial rapid development. In some instances, the ceilings continued to re-form and advect throughout the day. A summary of the meteorological characteristics of each event is given in Table 3.

The inversion strengths in Table 3 may be under-estimates of the actual magnitude because the sounding data interpolated to 1000-ft levels were used to obtain the values shown. In some instances, the inversions may have been less than 1000 ft deep and the interpolated sounding data may have consequently smoothed out the maximum magnitude of the inversions, especially for inversions based above the surface.

The meteorological characteristics that did not show discernable trends among the case days include the height of the low-level inversion, magnitude of the inversion, and the mean wind flow beneath the inversion. In each instance, a wide range of parameters was observed in both the event and non-event days. The height of the inversion ranged from surface-based to 7000 ft and the inversion strength varied from a 1.1°C increase in temperature to as high as 7.4°C. However, the strongest inversions tended to be surface-based from the morning sounding due to radiational cooling at the Earth’s surface. Finally, in all cases but two, the mean relative humidity beneath the inversion was generally greater than 80% (Table 3).

Table 3. **Summary of the 20 rapid low ceiling development events and accompanying meteorological characteristics. The mean quantities (relative humidity, wind direction and wind speed) are given for all levels at and below the base on the top-most inversion between the surface and 8000 ft. The wind direction change with height was determined by examining the sounding data from the surface to mid levels (~ 500 mb).**

Event Date	Onset Time (UTC)	Dissipation Time (UTC)	Highest Inversion Height (ft)	Inversion Strength (°C)	Mean RH (%)	Mean Flow (dirn@spd in kts)	Δ Wind Direction w/ Height
12/20/93	1500	1800	surface	7.1	91	0°@ 4	veering
11/4/94	1445	advected	4000	4.2	85	95°@ 13	slight veering
1/6/95	1745	1915	4000	2.2	85	135°@ 15	veering
3/10/95	1715	N/A	5000	2.6	75	39°@ 19	backing
11/13/95	1345	advected	5000	1.4	80	104°@ 3	slight veering
1/7/96	1345	1415	surface	2.6	94	213°@ 21	veering
2/21/96	1415	1745	surface	7.4	91	251°@ 9	veering
3/2/97	1415	1715	6000	6.3	94	177°@ 18	slight veering
3/30/97	1245	1545	surface	5.6	94	260°@ 2	slight backing
12/19/98	1345	1515	6000	4.7	84	153°@ 16	veering
1/30/99	1345	1815	6000	4.0	72	144°@ 9	veering
3/31/99	1215	1445	7000	1.1	90	127°@ 20	veering
1/30/01	1445	advected	6000	6.9	89	199°@ 31	veering
2/15/01	1300	1600	5000	1.6	81	211°@ 12	slight veering
12/4/01	1615	advected	6000	1.6	92	57°@ 13	negligible
2/26/03	1330	1430	surface	5.3	100	10°@ 2	veering
3/6/03	1245	1315	5000	3.7	78	198°@ 20	veering
2/20/04	1300	1400	4000	4.3	86	195°@ 11	veering
3/3/04	1215	1530	5000	4.6	86	125°@ 14	slight veering
1/6/05	1515	1715	6000	2.8	97	187°@ 14	slight veering

4.2 Comparison of Characteristics in Event/Non-Event Days

Since by definition, all 68 days had both low cloud ceilings at TTS and a stable, capped thermodynamic environment, one would expect that many meteorological characteristics were similar between the 20 rapid development days and the 48 non-development days. Figures 15 through 17 illustrate these common meteorological characteristics between event and non-event days. Both event and non-event days had a wide ranging inversion height (Figure 16), inversion strength (Figure 17), and generally had mean relative humidity above 70% (Figure 18). No distinguishable differences existed between any of these criteria. These conditions are simply the fundamental criterion needed for days that experience low cloud ceilings in east-central Florida under a stable regime.

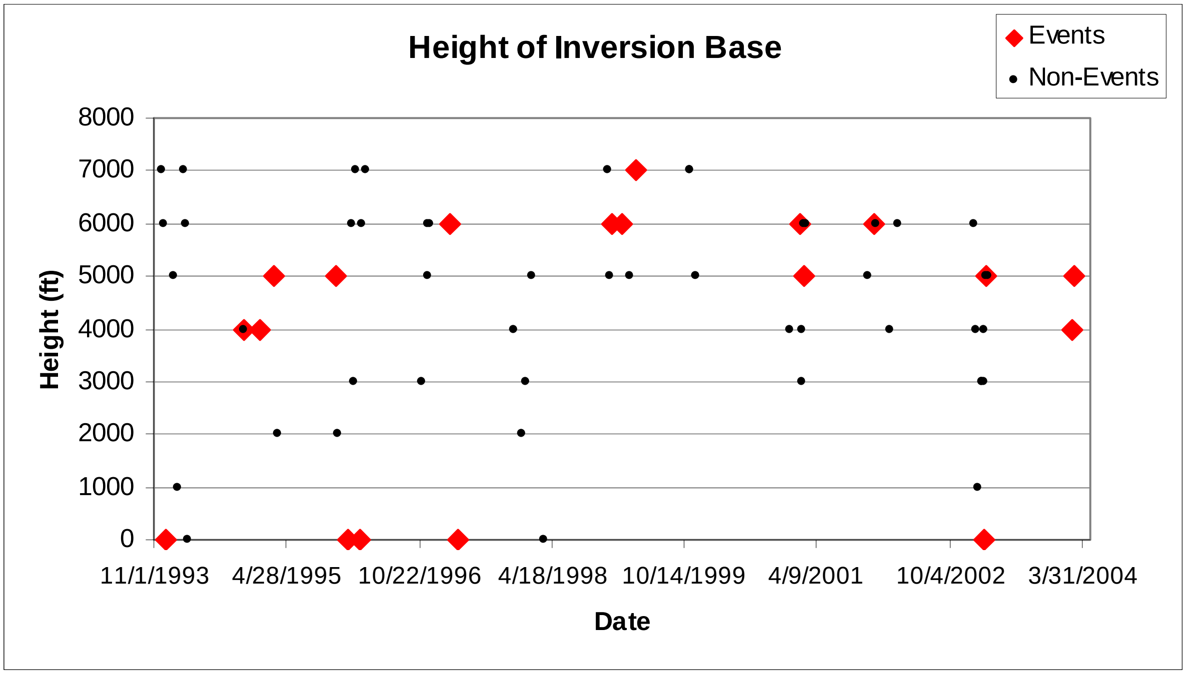

Figure 16. Scatter plot of the highest inversion heights (in ft) during event (large diamond) and non-event days (small circle).

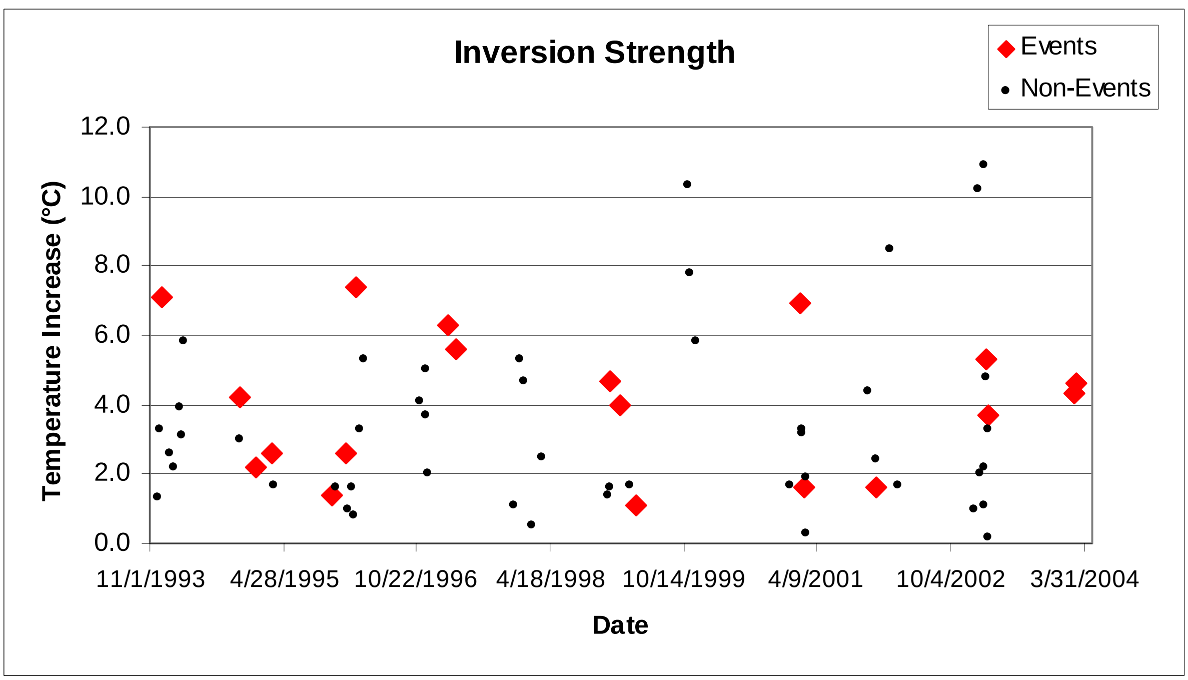

Figure 17. Scatter plot of the inversion strength (in °C) during event (large diamond) and non-event days (small circle).

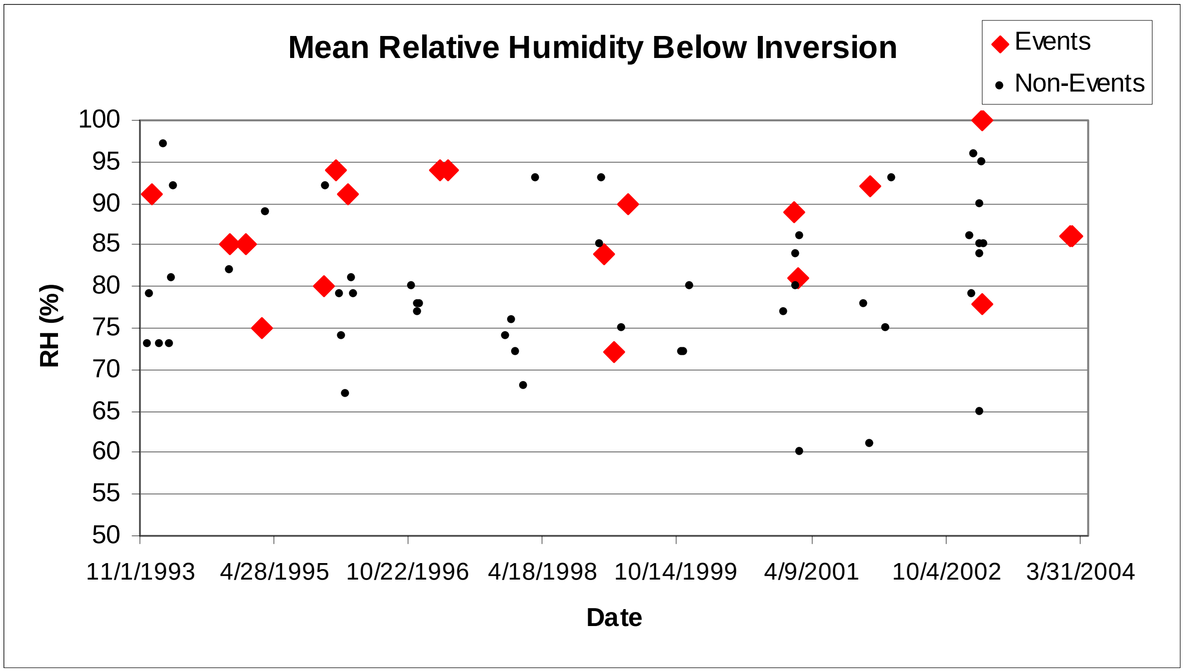

Figure 18. Scatter plot of the mean relative humidity (in %) below the inversion during event (large diamond) and non-event days (small circle).

The real challenge to the forecaster is discerning whether low cloud ceilings will form when ceilings do not already exist in this type of environment. Many of the 48 non-event days were classified as such after examining the visible satellite imagery. Most of these days had an obvious advection signature, typically off of the Atlantic Ocean, or else had widespread cloud ceilings that would be easy to discern as a "No-Go" condition. As stated in the 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 20 event days typically experienced rapid cloud formation in 30 minutes or less, with no prior extensive cloud decks present over east-central Florida.

Table 4 shows a summary of composite meteorological parameters for the 20 event days versus 48 non-event days. The most distinguishing characteristic between the event and non-event days is the vertical wind profile in the lower to middle troposphere. Seventeen of the 20 rapidly-developing, stable ceiling days had a veering wind profile representing a warm advection pattern that favors rising motion, and thus, cloud formation in a moist environment. Meanwhile, 40 of the 48 non-events had a backing vertical wind profile or negligible wind direction change with height, suggesting a post-frontal cold-advection pattern that would favor advection of clouds rather than development.

The other parameters listed in Table 4 are generally quite comparable to one another. The mean inversion height and strength are similar for the event and non-event days, while the mean relative humidity is slightly higher on the event days (87% vs. 80%). The statistical significance of the differences between event and non-event days was not tested for any of these parameters. However, the differences in the vertical wind profile for events versus non-events looks quite promising as a possible discerning factor. The veering wind profile also makes physical sense since veering winds contribute to large-scale rising motion and cloud development. However, the anomalies in the vertical wind profiles for events and non-events should be examined more closely to understand why the rapid ceiling development did or did not occur given the meteorological conditions on those days.

In order to develop a possible forecast tool from these findings, the robustness of the veering wind profile should be tested on all cool-season days for stable low cloud formation events from an expanded period of record. Any days that meet all the criteria for rapid low ceiling development should be tested for the occurrence of low ceilings at TTS. With an expanded database (including nocturnal cases), a statistical forecast method could be explored to determine the climatological probability for rapidly-developing ceilings, given that the meteorological conditions identified in this report are present. The performance of such a statistical tool should then be verified against an independent dataset.

Table 4. Summary of meteorological parameters associated with event and non-event days.

Parameter	Event days	Non-Event Days
# of days with winds backing with height or negligible directional shear	3 days (15%)	40 days (83%)
# of days with winds veering with height	17 days (85%)	8 days (17%)
Mean inversion height	4000 ft	4521 ft
Mean inversion strength	4.0°C	3.4°C
Mean RH below inversion	87%	80%

5 Summary and Future Work

This report described the AMU work done in developing a database of days that experienced rapid low cloud formation in a stable atmosphere, resulting in ceilings below 8000 ft at TTS. This report also documented the meteorological conditions favoring rapid, low cloud formation and the different conditions associated with event days and those days that had low cloud ceilings resulting from advection or some other mechanism.

The AMU examined data from the cool seasons in the period November 1993 to March 2003 for days that had low-level inversions and a rapid, stable low cloud formation that resulted in ceilings violating the Shuttle FR. The database was supplemented by three recent events identified by SMG that occurred during the course of this task. The AMU wrote and modified existing code to identify inversions from the morning XMR soundings during the cool season and output 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. Days with precipitation or noticeable fog burn-off situations were excluded from the database. Only the daytime hours were examined for possible cloud ceiling development events since low clouds are easier to diagnose with visible satellite imagery. Follow-on work could expand the database to include nighttime cases, using a special enhancement of the infrared imagery for identifying areas of low clouds.

Sample cases of rapidly-developing low cloud ceilings were presented. These cases depicted the representative meteorological and thermodynamic characteristics of such events. The cases also illustrated how quickly the cloud decks can develop, sometimes forming from one 15-minute satellite scan to the next.

Composite results were summarized for 20 event days with rapid low cloud ceiling formation and 48 non-events days consisting of advection or widespread low cloud ceilings. The rapid ceiling development for the daytime cases examined in this study occurred primarily in the morning hours between 1200–1800 UTC, indicating that heating and mixing probably played a role in the initial cloud formation. The meteorological conditions were quite similar for both the event and non-event days, as expected, since both types of days experienced low cloud ceilings. Both types of days had a relatively moist environment beneath an inversion based below 8000 ft.

The distinguishing factor between the ordinary low cloud ceilings days, and the days that had rapid development appears to be the vertical wind profile in the XMR sounding. Eighty-five percent of the event days had veering winds with height in the lower to middle troposphere whereas 83% of the non-events had backing or negligible wind direction change with height. Veering winds indicate a warm-advection regime, which supports large-scale rising motion and ultimately cloud formation. Meanwhile, backing winds with height indicates cold advection or sinking motion in a post-cold frontal environment. The advection of low cloud ceilings typically occurs in a post-cold frontal regime when cool air passes over the warmer Atlantic Ocean, generating a stratocumulus deck that can move into east-central Florida.

Future work could involve expanding the database by including nocturnal cases, identified using a special enhanced infrared imagery. The database could be further expanded by increasing the period of record to earlier years. In addition, the study could be extended to other Shuttle landing sites if sufficient surface and rawinsonde data sets are available.

Most importantly, the robustness of the meteorological criteria identified in this report as possible predictors (i.e. low-level inversion, high boundary-layer relative humidity and veering wind profile) should be tested on all cool-season days from the study's period of record for stable low cloud formation. Any days that meet all these criteria should be tested for the occurrence of rapid low ceiling development at TTS. With an expanded database (including nocturnal cases), a statistical forecast method could be explored to determine the climatological probability for rapidly-developing ceilings, given that the meteorological conditions identified in this report are present. The performance of such a statistical tool should then be verified against an independent dataset.

Finally, the cessation of low ceilings during rapid-development events could be examined to determine the predictability of timing the end to the low ceiling violations. Once the ceilings have formed, it would be helpful if the forecaster had confidence in the dissipation time. A tool such as the Wind Stratified Conditional Climatology developed by AFCCC may be helpful in providing guidance for the cessation of low ceilings. The AMU could modify or tune such a tool using an expanded database of rapidly-developing ceilings events containing both daytime and nocturnal events.

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List of Abbreviations and Acronyms

Term	Description
45 WS	45th Weather Squadron
AFCCC	Air Force Combat Climatology Center
AMU	Applied Meteorology Unit
APU	Auxiliary Power Unit
CCAFS	Cape Canaveral Air Force Station
EDW	Edwards Air Force Base, CA station identifier
EOM	End Of Mission
FR	Flight Rules
ft	feet
ID	Identifier
JSC	Johnson Space Center
KSC	Kennedy Space Center
kts	knots
McIDAS	Man computer Interactive Data Access System
NOR	White Sands Space Harbor, NM station identifier
NWS	National Weather Service
PLS	Primary Landing Site
RH	Relative Humidity
RTLS	Return To Launch Site
SMG	Spaceflight Meteorology Group
TAL	Trans-oceanic Abort Landing
TTS	Shuttle Landing Facility station identifier
UTC	Coordinated Universal Time
XMR	Cape Canaveral, FL rawinsonde station identifier

NOTICE