P3.2 A STUDY OF RAPIDLY DEVELOPING LOW CLOUD CEILINGS IN A STABLE ATMOSPHERE AT THE FLORIDA SPACEPORT

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1. INTRODUCTION

Forecasters at the Spaceflight Meteorology Group (SMG) have responsibility for issuing space shuttle landing forecasts for standard and abort landing scenarios. These scenarios include Return to Launch Site abort landings at the Shuttle Landing Facility (METAR identifier TTS) within the Kennedy Space Center (KSC), abort-once-around at the primary landing site, trans-oceanic abort landings, and standard End Of Mission at KSC, Edwards Air Force Base, CA, and White Sands Space Harbor, NM (Brody et al. 1997). A variety of space shuttle flight rules 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). These flight rules were designed to avoid hazardous weather and ensure the safe return of the orbiter.

SMG forecasters issue 30 to 90 minute predictions of restricted cloud ceilings at TTS to support landing scenarios at KSC. Verification statistics have shown ceilings to be the number one forecast challenge. SMG forecasters are particularly concerned with any rapidly developing low-level cloud ceilings in a stable thermodynamic environment.

The Applied Meteorology Unit (AMU) was tasked to examine archived events of rapid stable cloud formation resulting in low restricted ceilings, and document the weather regimes favoring this type of cloud development. The AMU was asked to distinguish between cloud advection and development cases, since SMG forecasters can already handle advection situations. This paper focuses on the cloud ceiling flight rule that applies to the KSC landing site. The most commonly encountered cloud ceiling height restriction for shuttle missions is 2438 m (8000 ft), which is the focus of this study.

The objective of this project was to identify and examine days with rapidly developing cloud ceilings below 2438 m occurring 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 2438 m, identify the onset and dissipation times, and document the atmospheric regimes favoring the rapid, stable cloud formation.

The remainder of this paper 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 a rapidly-forming low ceiling event. Section 4 presents the composite atmospheric characteristics that favor stable cloud ceiling formation, and Sections 5 and 7 provide a summary and references, respectively.

2. METHODOLOGY

SMG indicated that these events often take place in the cool season 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 (identifier 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 large number of cool-season days to examine for stable low-cloud formation, the AMU devised an objective method to parse through all data and retain only days with a low-level inversion combined with observed cloud ceilings below 2438 m 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 Science Raytheon for the months and years listed above. The AMU then developed software to identify inversions below 2438 m 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 305 m (1000 ft) beginning at the surface up to 2438 m including 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 study, as well as provide output for assessing potential rapid low-cloud development events.

2.2 Identify Low Cloud Ceilings

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Archived surface observations were obtained from the Air Force Combat Climatology Center (AFCCC) for all central Florida METAR sites for the period of record. Software was developed to read in the AFCCC-formatted data and parse out the pertinent cloud information from the archived METAR reports. The TTS archived data were first processed in order to obtain a record of cool-season days with low cloud ceilings that violated the cloud ceiling flight rule for shuttle landings at KSC.

The program was designed to output any reports of cloud ceilings and their accompanying height below 2438 m 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 ceilings from those associated with fog burn-off and/or precipitation.

The days with both low-level inversions and low ceilings at TTS were then combined into a common Excel spreadsheet for further examination. Data from several nearby central Florida METAR stations were then processed to compare their 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.

2.3 Develop Database of Possible Events

A subjective analysis of the output was then conducted to identify potential case days. Through this subjective analysis, the database was further narrowed to exclude precipitation events, days with ceilings resulting from early morning fog, and days with ceilings below 2438 m all day, since the goal of the study is to study the ceiling formation, not just overall occurrences. Days were identified as potential events if they exhibited each of the following three elements: (1) a low-level inversion, (2) high relative humidity near and below the inversion, and (3) a ceiling below 2438 m. 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 with low ceilings 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 first 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.

3. 30 JANUARY 1999 EVENT

Florida weather 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 Ocean to Jacksonville, FL, and to a low pressure center near the Oklahoma / Arkansas border (Figure 1). This pattern resulted in a stable atmosphere across central Florida with a light wind out of the east near KSC/CCAFS. Surface temperatures were around 16°C across central Florida.

The morning rawinsonde at XMR had two inversions present (Figure 2). The first was at the surface due to the radiational cooling that had taken place overnight. Another was located between 800 and 770 mb. Winds just above the surface inversion were out of the southeast at 8 m s^{-1} and then veered 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 3). This day, however, had ceilings that advected from the northeast off of the Atlantic Ocean rather than developed. The thermodynamics 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 with height on the 30 January event while the winds backed with height on the 8 March non-event. The possible 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 (Fig. 4a). Thirty minutes later, a few scattered clouds began forming over KSC/CCAFS but were not sufficient to cause ceilings (Fig. 4b). However, by 1345 UTC, low clouds and subsequent ceilings had rapidly developed over the KSC/CCAFS area and adjacent coastal waters (Fig. 4c).

This case shows 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 study. The next section summarizes the composite results of all rapidly developing low ceiling events, and compares/contrasts the meteorological and thermodynamic conditions of event days to non-event days when low ceilings existed, but did not rapidly form.

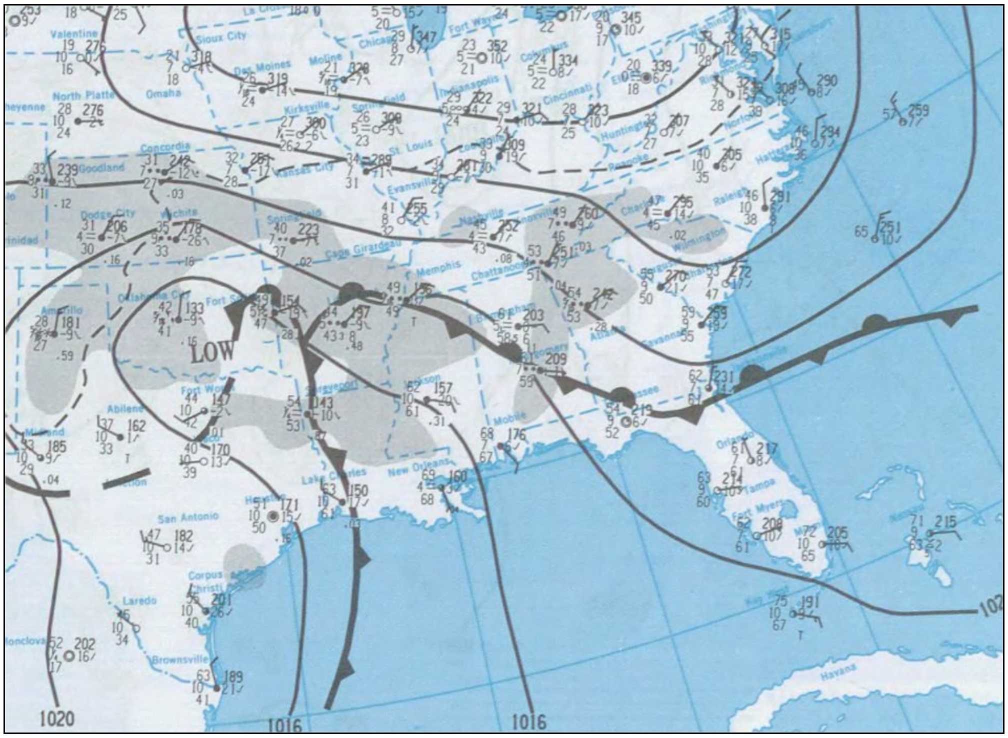

Figure 1. Surface analysis at 1200 UTC 30 January 1999.

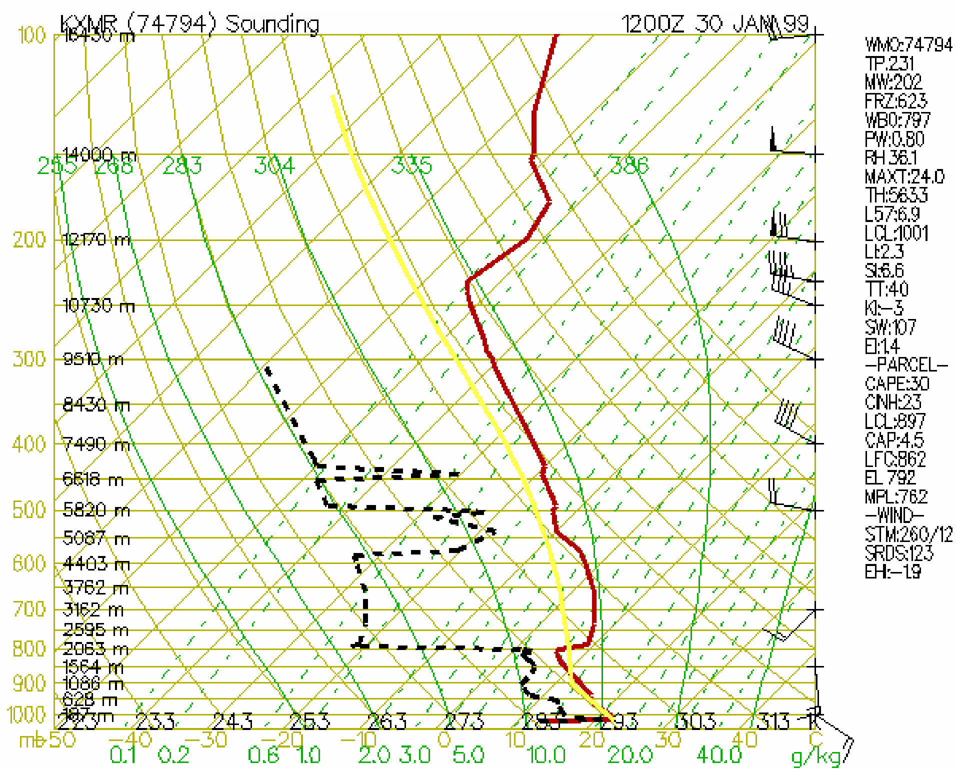

Figure 2. XMR rawinsonde at 1200 UTC 30 Jan 1999. Note the fairly high moisture beneath the strong inversion near 800 mb, and veering winds from the surface up to 500 mb.

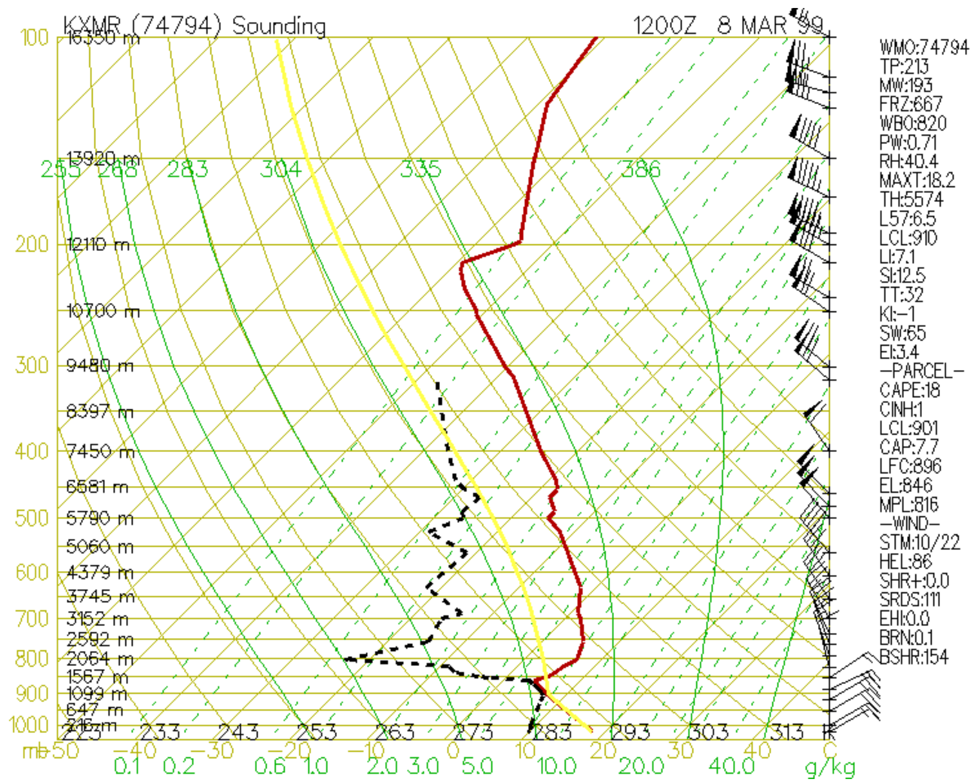

Figure 3. XMR rawinsonde at 1200 UTC 8 Mar 1999. Note the fairly high moisture beneath the inversion near 850 mb, and backing winds from the surface up to 500 mb.

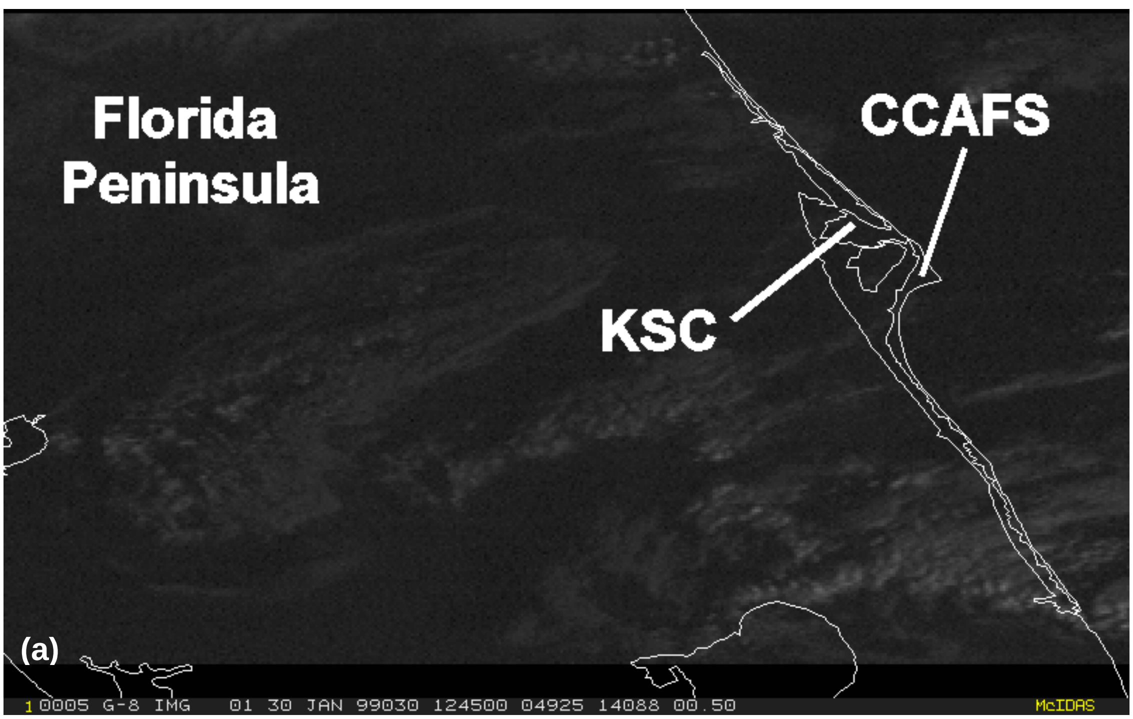

Figure 4. Visible satellite imagery from 30 January 1999, valid at (a) 1245 UTC, (b) 1315 UTC, and (c) 1345 UTC.

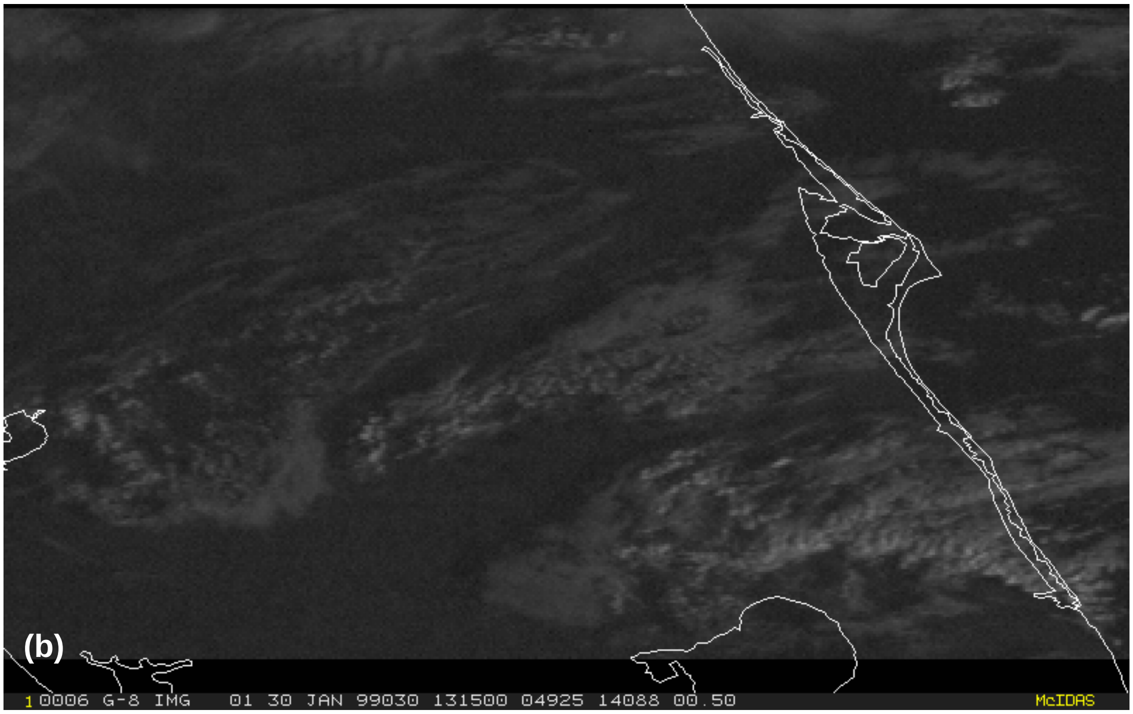

Figure 4, cont.

4. COMPOSITE RESULTS

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 Low Ceiling Development Events

By definition, the rapid, stable low cloud development days consisted of a stable low-level sounding with an inversion present below 2438 m. Other characteristics include formation times between 1200–1800 UTC, a relatively moist 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 be from a southerly and/or easterly component, but varied quite substantially from case to case.

A summary of the meteorological characteristics of each event is given in Table 1. The inversion strengths in Table 1 may be under-estimates of the actual magnitude because the sounding data interpolated to 305-m levels were used to obtain the values shown. In some instances, the inversions may have been less than 305 m 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 any 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 all the different development events. The height of the inversion ranged from surface-based to 2134 m 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, as one might expect during the Florida cool season. Finally, in all cases but two, the mean relative humidity beneath the inversion was generally greater than 80% (Table 1).

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 4 through 6 illustrate these common meteorological characteristics between event and non-event days. Both event and non-event days had a wide ranging inversion height (Figure 5), inversion strength (Figure 6), and generally had mean relative humidity above 70% (Figure 7). No distinguishable differences existed between any of these criteria. These conditions are simply the fundamental criteria needed for days with low cloud ceilings in east-central Florida under a stable regime.

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 for a space shuttle landing at KSC. 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 case days typically experienced rapid cloud formation in 30 minutes or less time, with no prior extensive cloud decks present over east-central Florida.

Table 2 shows a summary of meteorological parameters for the 20 case days versus 48 non-case days. The most distinguishable 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. Such a profile represents 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 2 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.

Table 1. 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 inversion. 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 (m)	Inversion Strength (°C)	Mean RH (%)	Mean Flow (dirn@spd in m s^{-1})	Δ Wind Direction w/ Height
12/20/93	1500	after 1800	surface	7.1	91	0°@ 2	veering
11/4/94	1445	advected	1219	4.2	85	95°@ 7	slight veering
1/6/95	1745	1915	1219	2.2	85	135°@ 8	veering
3/10/95	1715	N/A	1524	2.6	75	39°@ 10	backing
11/13/95	1345	advected	1524	1.4	80	104°@ 2	slight veering
1/7/96	1345	1415	surface	2.6	94	213°@ 11	veering
2/21/96	1415	1745	surface	7.4	91	251°@ 5	veering
3/2/97	1415	1715	1829	6.3	94	177°@ 9	slight veering
3/30/97	1245	1545	surface	5.6	94	260°@ 1	slight backing
12/19/98	1345	1515	1829	4.7	84	153°@ 8	veering
1/30/99	1345	1445	1829	4.0	72	144°@ 5	veering
3/31/99	1215	1445	2134	1.1	90	127°@ 10	veering
1/30/01	1445	advected	1829	6.9	89	199°@ 16	veering
2/15/01	1300	1600	1524	1.6	81	211°@ 6	slight veering
12/4/01	1615	advected	1829	1.6	92	57°@ 7	negligible
2/26/03	1330	1430	surface	5.3	100	10°@ 1	veering
3/6/03	1245	1315	1524	3.7	78	198°@ 10	veering
2/20/04	1300	1400	1219	4.3	86	195°@ 6	veering
3/3/04	1215	1530	1524	4.6	86	125°@ 7	slight veering
1/6/05	1515	1715	1829	2.8	97	187°@ 7	slight veering

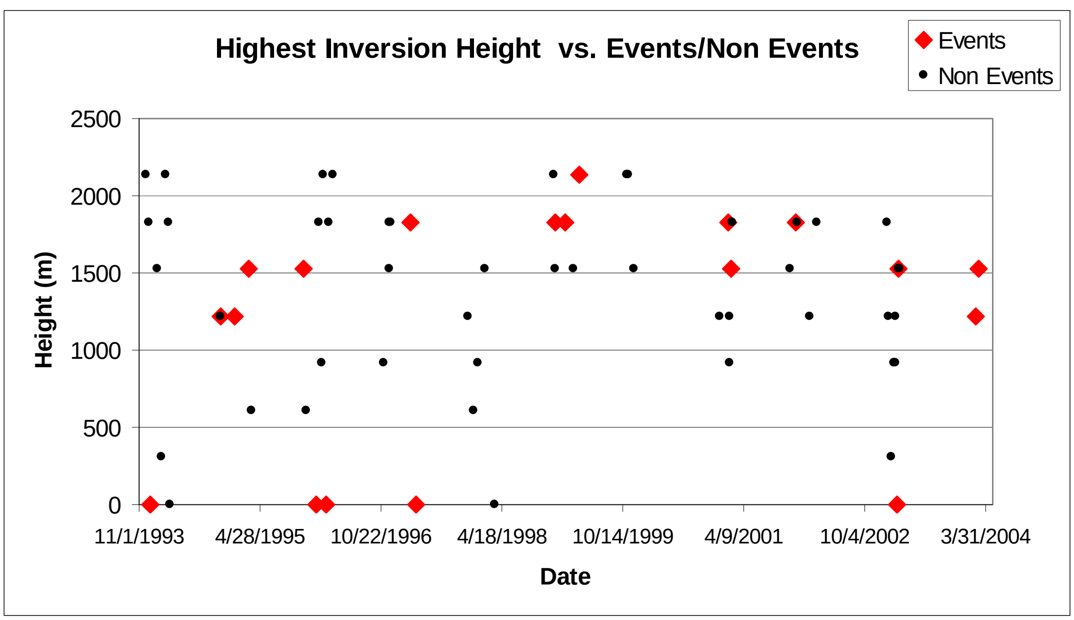

Figure 5. Scatter plot of the highest inversion heights (m) during event (large diamond) and non-event days (small circle).

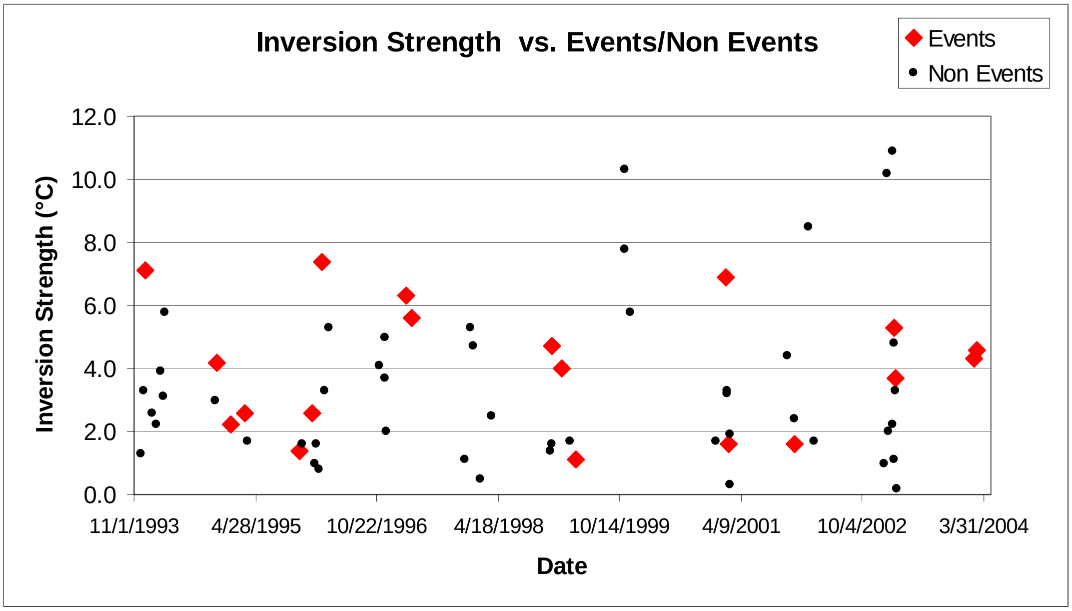

Figure 6. Scatter plot of the inversion strength (in °C) during event (large diamond) and non-event days (small circle).

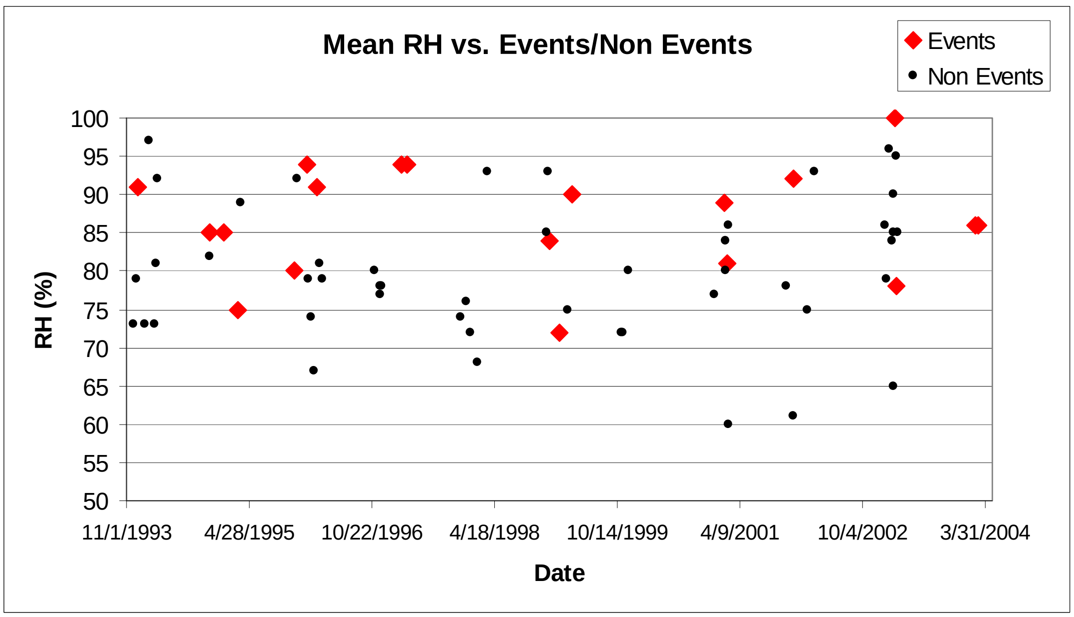

Figure 7. Scatter plot of the mean relative humidity (in %) below the inversion during event (large diamond) and non-event days (small circle).

Table 2. 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	1219 m	1378 m
Mean inversion strength	4.0°C	3.4°C
Mean RH below inversion	87%	80%

5. SUMMARY

This paper 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 2438 m at TTS. The paper also documented the meteorological conditions favoring rapid, low ceiling formation.

Meteorological parameters were summarized for 20 days with rapid low cloud ceiling formation and 48 non-event days consisting of advection or widespread low cloud ceilings. 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 2438 m.

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 in a moist environment. Meanwhile, backing winds with height indicates cold advection or sinking motion in a post-cold frontal environment.

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7. REFERENCES

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