NASA Contractor Report NASA/CR-2002-211170

Improved Anvil Forecasting:
Phase II Final Report

Prepared by:
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

2002

ATTRIBUTES AND ACKNOWLEDGMENTS:

NASA/KSC POC:
Dr. Francis J. Merceret
YA-D

Applied Meteorology Unit (AMU):

David A. Short
Mark M. Wheeler

Executive Summary

Electrified thunderstorm anvil clouds extend the threat of natural and triggered lightning to space launch and landing operations far beyond the immediate vicinity of thunderstorm cells. The deep convective updrafts of thunderstorms transport large amounts of water vapor, super-cooled water droplets and ice crystals into the upper-troposphere, forming anvil clouds, which are then carried downstream by the prevailing high-level winds. Electrified anvil clouds have been observed over the space launch and landing facilities of Kennedy Space Center (KSC) and the Eastern Range, emanating from thunderstorm activity more than 100 nautical miles (nmi) distant. It is non-transparent portion of the anvil cloud that poses the threats of natural and triggered lightning and is to be avoided by launch and landing vehicles.

The 45th Weather Squadron (45 WS) Launch Weather Officers (LWO) and the Spaceflight Meteorology Group (SMG) forecasters have identified anvil forecasting as one of their most challenging tasks when predicting the probability of violations to the Launch Commit Criteria and Space Shuttle Landing Flight Rules. Phase I of this task established the technical feasibility of developing an objective, observations based technique for short-term anvil forecasting. The purpose of this Phase II effort was to develop and document a short-term/now-cast technique for anvil forecasting for the 0-12 hour time period and a next-day forecast model for the 12-36 hour time period.

Work on this study was separated into three steps: data collection/archiving, data analysis, and forecast tool development. Data collection and archiving were required to increase the number of anvil cases and to improve the statistical reliability of analysis results. The analysis portion of the task was required to determine statistical parameters such as the propagation and lifetime characteristics of anvil clouds over Florida. All the derived information was incorporated into the design, construction and implementation of an objective short-range anvil forecast tool based on upper-air observations.

Anvil clouds were found to move at the speed and direction of the upper-level winds in the layer between 300 and 150 mb, approximately 31 000 to 46 000 ft, with an effective average transport lifetime of 2 hours and a standard deviation of 30 minutes. The effective lifetime refers to the time required for the nontransparent leading edge of an anvil cloud to reach its maximum extent before dissipating.

The AMU developed a prototype graphical short-term anvil-forecasting tool for use on the Meteorological Information Data Display System (MIDDS) and demonstrated it to 45 WS and SMG customers during a technical interchange meeting in November 2001. Using a single command line, the forecaster is provided with a visual image of an anvil threat sector centered on a user-selected station and extending upstream, according to the upper-level wind speed and direction. Wind speed and direction information is automatically calculated from the latest radiosonde data for the station of interest. Additional functionality allows the forecaster to manually input wind speed, wind direction and desired latitude/longitude coordinates.

Refinement of the short-term observations-based prototype forecast tool was accelerated in response to customer input, following a telephone conference in December 2001. Their request was to have the tool available for implementation on the operational MIDDS in Range Weather Operations and SMG by the end of February 2002 and to forego development of a longer range forecast technique until the completion of testing and familiarization by 45 WS LWOs and SMG forecasters.

THIS PAGE INTENTIONALLY LEFT BLANK.

Table of Contents

List of Figures

List of Tables

List of Acronyms

Term	Description
45 WS	45th Weather Squadron
ABFM	Airborne Field Mill
AMU	Applied Meteorology Unit
BASIC	Beginner's All-purpose Symbolic Instruction Code
CCAFS	Cape Canaveral Air Force Station
CGLSS	Cloud-to-Ground Lightning Surveillance System
CRYSTAL	Cirrus Regional Study of Tropical Anvils and Cirrus Layers
EDT	Eastern Daylight Time
FACE	Florida Area Cirrus Experiment
FR	Flight Rules
GOES	Geostationary Operational Environmental Satellite
KSC	Kennedy Space Center
kts	knots
LAP	Lightning Advisory Panel
LCC	Launch Commit Criteria
LPLWS	Launch Pad Lightning Warning System
LWO	Launch Weather Officer
McIDAS	Man Computer Interactive Data Access System
McBASI	McIDAS BASIC Language Interpreter
POC	Point of Contact
MHz	Mega Hertz
MIDDS	Meteorological Interactive Data Display System
MLB	Melbourne, Florida
mb	millibar
nmi	nautical mile
NWS	National Weather Service
RUC	Rapid Update Cycle
RWO	Range Weather Operations
SLC	Space Launch Complex
SLF	Shuttle Landing Facility
SMG	Spaceflight Meteorology Group
UTC	Coordinated Universal Time
VVSTORM	Vertical Velocity Storm
XMR	CCAFS weather station 3-letter identifier

1. Introduction

Launch Weather Officers (LWOs) from the 45th Weather Squadron (45 WS) and forecasters from the Spaceflight Meteorology Group (SMG) have identified anvil forecasting as one of their most challenging tasks when predicting the probability of violations to the lightning Launch Commit Criteria (LCC) and Space Shuttle Landing Flight Rules (FR). As a result, the Applied Meteorology Unit (AMU) was tasked to develop an objective technique for forecasting the propagation characteristics of thunderstorm anvil clouds and to provide training in its use by LWOs and forecasters. Phase I of this study established the technical feasibility of developing a successful observations-based forecasting technique, given the promising relationships found by the 45 WS between anvil length and lifetime and the average wind speed/direction and moisture content in the anvil layer (Lambert 2000).

The original plan for this Phase II effort called for the AMU to build upon the results of Phase I with a data collection and archiving campaign to increase the sample of anvil cases, and to improve the reliability of resulting statistics. The campaign was to be followed by data analysis, and development of objective methodologies to forecast the occurrence of anvil clouds over the Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) area on two time scales: a short term, 0- to 12-hour time period and a next-day, 12- to 36 hour time period. Forecasts for the short-term time period were to make use of observational data, whereas the 12- to 36-hour forecast was to incorporate information from numerical weather prediction models.

The AMU completed the data collection and archiving, and analysis portions on schedule and proceeded with the development of a short-term graphical forecast tool. The prototype tool was demonstrated to customers during a technical interchange meeting in November 2001. Refinement of the prototype was accelerated in response to customer input, following a telephone conference in December 2001. The customers requested that the AMU have the short-term tool ready for implementation on the operational Meteorological Interactive Data Display System (MIDDS) in the Range Weather Operations (RWO) facility by the end of February 2002. The customers also directed the AMU to forego development of a longer range (12-36 h) technique until 45 WS LWOs and SMG forecasters completed testing of and familiarization with the short-term tool.

This report contains detailed descriptions of the data collection/archiving effort, the data analysis results, and the development of the automated graphical short-term forecast tool. Additional information on the implementation and use of the forecast tool is included.

1.1. Anvil Electrification Hazard

Electrified thunderstorm anvil clouds extend the threat of natural and triggered lightning to space launch and landing operations far beyond the immediate vicinity of thunderstorm cells (Roeder et al. 1999). Anvil clouds are formed in the upper-troposphere from a supply of water vapor, super-cooled cloud droplets, and ice crystals that are carried aloft by deep convective updrafts. They are then carried downstream by upper-tropospheric winds (Detwiler and Heymsfield 1987) and can serve as conduits for lightning originating from their parent thunderstorms.

Electrified anvil clouds have been observed over the space launch and landing facilities of KSC and CCAFS emanating from thunderstorm activity more than 100 nmi distant. Mature anvils and even detached anvils can remain electrically charged for several hours, posing the additional threat of triggered lightning if penetrated by a launch or landing vehicle (Garner et al. 1997).

Charging mechanisms in anvil clouds are complex; however, the general structure is a positively charged center surrounded by negatively charged exterior screening layers above and below (Marshall et al. 1989). The screening layers can have an adverse effect on the ability of the Launch Pad Lightning Warning System (LPLWS) to detect electrification in an anvil cloud above the network.

Real-time operational decisions are based on the need for launch and landing vehicles to avoid the optically non-transparent portions of anvil clouds. The Lightning Advisory Panel (LAP; Krider et al. 1999) has developed a comprehensive set of lightning LCC for all space launches. Space Shuttle FR were developed by the Johnson Space Center Mission Operations Directorate, using the lightning LCC as guidance. The lightning LCC and FR are used by LWOs and SMG forecasters to assure that flight vehicles remain well clear of potentially hazardous anvil clouds. Refer to Appendix A in Lambert (2000) for a description of the lightning LCC and FR.

Figure 1 shows a satellite image of thunderstorm anvil clouds that forced the launch of STS-105 to be postponed on the afternoon of 9 August 2001. The optically non-transparent anvil clouds had drifted slowly southeastward, as estimated from the satellite images, in a light, northwest upper-level wind from thunderstorm cells located 30 to 50 nmi northwest of the launch pad. The anvil cloud has covered launch pad 39A and the Shuttle Landing Facility (SLF), violating the lightning LCC.

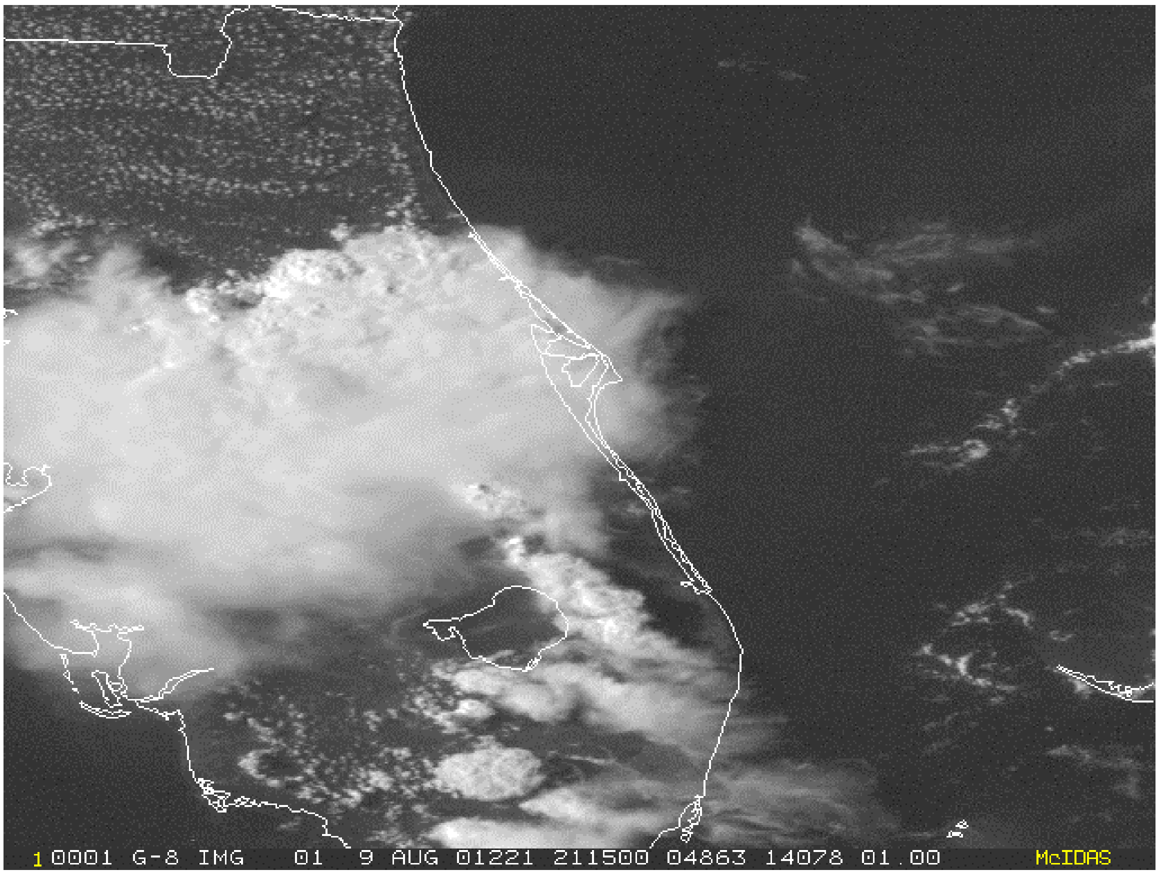


Figure 1. A GOES-8 visible image at 2115 UTC (1715 EDT) on the afternoon of 9 August 2001. Anvil clouds that forced the STS-105 launch to be postponed can be seen over the Cape Canaveral area (center of the image), emanating from a thunderstorm complex to the northwest.

1.2. Overview of Phase I Findings

Lambert (2000) documented the results of a literature search, forecaster discussions and a feasibility study. A search of the operational and scientific literature revealed no existing, formally documented anvil-forecasting techniques. However, a growing interest in the microphysical, electrical and radiative properties of anvil clouds was evident in recent years. Discussions with forecasters revealed methods on how anvil forecasting is done currently and how better techniques could be developed. Operational forecasters provided ideas based on meteorological principles and personal experience in forecasting and analyzing anvils. A technique proposed by Mr. Jim Sardonia, a 45 WS LWO, using observational data showed promising relationships between the upper-level wind and moisture fields and anvil length and lifetime. SMG proposed a modeling study to determine what meteorological parameters are important for anvil formation. It was also determined that a modeling study may help define what data are needed to develop an observation-based forecasting tool.

Based on the information gathered in the discussion with the forecasters, the conclusion was that it would be technically feasible to develop an anvil forecasting technique that would contribute to the confidence in anvil forecasts. The forecasters suggested an observations-based study and two types of modeling studies. The likelihood of success for a modeling based study was judged to be unknown, due to the lack of knowledge of model skill in simulating high level moisture associated with the life cycle of thunderstorm anvils. The likelihood of success of an observations technique was determined to be high and the AMU recommended that Phase II start with a data collection effort to expand the number of anvil cases available for analysis. The AMU would then proceed to explore statistical and physical relations in the expanded data set in order to guide the development of an observations-based forecasting technique.

1.3. Overview of Phase II Objectives

The objectives of the present study were to increase the sample size of anvil cases by archiving routinely available observations and model output, to analyze the resulting database for anvil cases and to develop anvil forecast techniques. The techniques were requested by 45 WS LWOs and SMG forecasters to assist them in predicting probable violations of the triggered lightning LCC and Space Shuttle FR.

The original task plan called for development of forecast methodologies focusing on two time scales: A short-range/nowcast technique for the 0- to 12-hour time period and a next day forecast model for the 12- to 36-hour time period. The short-range/now-cast technique was to make use of all relevant observational data, including hourly analyses from the Rapid Update Cycle (RUC) model. In addition, hourly updates to the RUC 3-hour forecasts, 3-hourly updates to the RUC 12 hour forecast, and 0- to 12-hour Eta model forecasts were to be used for short-term numerical guidance. The 12- to 36-hour forecast model was to make use of forecast wind, vorticity, upper-level divergence, vertical motion and moisture fields from the Eta model. All relevant observational data were to be used to assess observed anvil conditions associated with dynamical features that are forecast to affect the KSC/CCAFS area within 12 to 36 hours.

The AMU continued its dialog with forecasters from the 45 WS, SMG and the National Weather Service Office at Melbourne (NWS MLB) regarding procedures for forecasting the occurrence of anvil clouds over KSC/CCAFS. This has resulted in an observations-based forecast tool that can be used by 45 WS LWOs and SMG forecasters in an operational environment on a day-to-day basis.

It should be noted that refinement of the observations-based prototype forecast tool was accelerated in response to customer input, following a telephone conference in December 2001. Their request was to have the tool available for implementation on the operational system by the end of February 2002 and to forego development of longer range forecast tools pending testing and familiarization by 45 WS LWOs and SMG forecasters. The resulting tool has a help function and this final report includes a section for training forecasters in its use.

1.3.1. Observational Study

The purpose of the observational study was to determine physical characteristics of thunderstorm anvil clouds over Florida. Properties such as propagation characteristics, transport lifetimes and their statistical variability were needed for the development of objective anvil forecasting tools. The pilot study carried out by Mr. Jim Sardonia of the 45 WS and documented by Lambert (2000) served as a baseline for the AMU observational study. The pilot study established a strong correlation between anvil length, wind speed and humidity information in the anvil layer between 300 and 150 mb. The AMU observational study added wind direction in the 300- to 150-mb layer and wind speed/direction in the 900- to 500-mb layer.

1.3.2. Forecast Tool Development

The results from Phase I and the 45 WS pilot study revealed useful linear relationships between atmospheric wind speed and humidity values and anvil characteristics such as transport distance and transport lifetime. Such relationships can be used to define a "threat corridor" upwind of the KSC/CCAFS area. If thunderstorms form within the threat corridor, forecasters can infer an increased probability for anvils to occur over the KSC/CCAFS area. This technique, referred to as an extrapolation/advection method, requires an accurate analysis of the wind speed and direction in the upper-tropospheric layer that would contain the anvil cloud. The objective is to develop graphical tools that will use meteorological information routinely available in the operational environment, such as upper-level wind and moisture information from radiosonde observations and forecast models.

2. Data Collection and Analysis

The objectives of the data collection and analysis portion of this task were to expand the database of 17 anvil case days documented in Phase I and to add additional information needed to formulate an objective anvil forecast tool. Dr. Short and Mr. Wheeler developed a list of routinely available satellite, forecast model and surface and upper-air data to be archived on a daily basis beginning in May 2001. The data-type list was based on results of the Phase I study and discussions with forecasters from the 45 WS, SMG and the NWS MLB. Mr. Wheeler created daily file transfer scripts to download gridded and point data from the Eta forecast model, analysis and forecast data from the RUC model, and sounding data from the Geostationary Operational Environmental Satellite (GOES), number 8 (GOES-8). He also developed routines for archiving visible and infrared digital imagery from GOES-8, lightning data from the Cloud-to-Ground Lightning Surveillance System (CGLSS), and surface observations through the MIDDS. The resulting data archive for the months of May, June and July 2001 has provided an additional 50 case days for the task.

2.1 Methodology

The AMU followed the analysis procedure developed by Mr. Sardonia of the 45 WS in a pilot study of anvil clouds conducted during 1999 and 2000 and documented by Lambert (2000). The procedure was to use visible satellite imagery to determine the horizontal extent of mature anvils, where mature indicates the time when the non-transparent portion of the anvil reaches its maximum horizontal extent. Radiosonde data were used to determine upper-level winds and humidity in the anvil layer. Mr. Sardonia's pilot study established a correlation between anvil length and wind speed in the layer between 300 and 150 mb. The AMU added five more parameters to this study.

- The direction from the point where the parent thunderstorm complex originated to the end of the mature anvil,
- Coordinates of the point where the parent thunderstorm originated,
- The wind direction in the upper-tropospheric layer,
- The wind speed in a lower-tropospheric layer from 900 to 500 mb, and
- The wind direction in the lower-tropospheric layer.

The lower-tropospheric layer was added to include information affecting the motion of thunderstorms during their formative stages.

An anvil case day was defined as one in which the generation and dissipation of at least three separate anvil clouds was clearly evident and measured from satellite imagery, consistent with Mr. Sardonia's study. For the purposes of this study, the life history of an anvil cloud commenced when it first became visible above a thunderstorm complex, and was considered complete when its leading non-transparent edge reached a maximum horizontal distance from the point of origin. Determination of the location of the non-transparent edge was based on personal experience and was subject to an error estimated to be about 20 km. The error is a small fraction of the natural variability associated with observed anvils clouds and is not a significant factor in the analysis. At times, anvil-type clouds less than 30-km long were seen in two or three consecutive frames of the GOES-8 visible imagery. Features of this type are associated with isolated thunderstorm cells and do not pose the long-range, long-term threat associated with the anvil clouds included in the analysis presented here.

2.1.1 Satellite Imagery

Anvil cloud properties were measured subjectively in an analysis of visible imagery from channel 1 on GOES-8 (0.55-0.75 μm) with a spatial resolution of 1 km. GOES-8 data were archived every 15 to 30 minutes and analyzed using the Man-Computer-Interactive-Data-Access-System (McIDAS). The McIDAS software provides the user with customized image enhancement capabilities that facilitate interpretation of cloud features in the satellite imagery. Anvil clouds originating from small clusters of thunderstorms are readily evident in time loops of visible imagery. These anvil clouds, classified as *cirrostratus cumulonimbogenitus*, rapidly expand tens of kilometers or more in a manner consistent with the wind flow in the upper-troposphere, in the layer from about 300 to 150 mb. The anvil cloud is highly reflective to visible radiation during its growing and mature phases, obscuring views of the surface and lower clouds. Infrared imagery (channel 4, 10.2-11.2 μm) indicates radiative temperatures less than 240K at the tops of anvil clouds, consistent with atmospheric temperatures in the upper-troposphere.

Figure 2 shows a sample image from the Phase I study depicting the measurement of the length of a mature anvil. Determination of the point where the anvil transitions from non-transparent to transparent was subjective, however consistent evaluation was enabled by use of MIDDS image enhancement functions allowing the user to determine if lower clouds or surface features were visible through the anvil cloud.

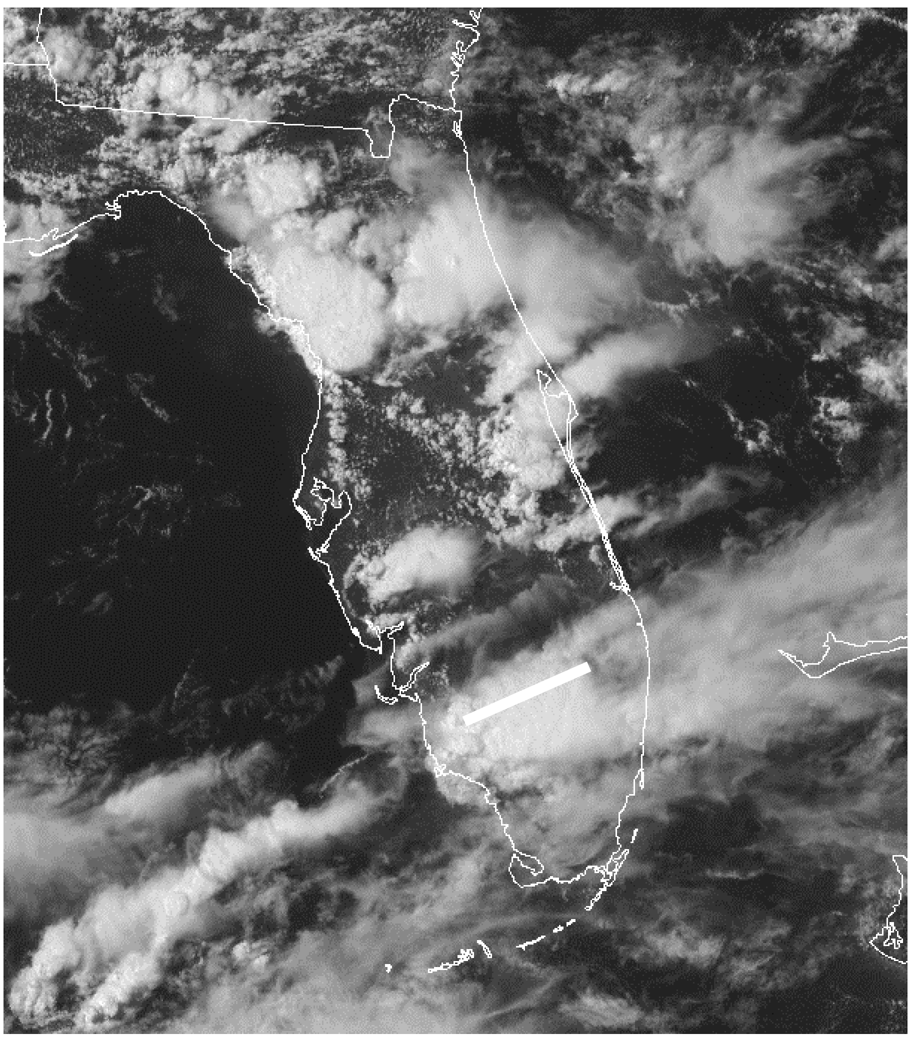


Figure 2. GOES-8 visible image from 12 June 1999 at 2000 UTC (1600 EDT). The line represents the transport distance of the non-transparent anvil at its maximum length from the parent storm to the non-transparent edge.

Within one to three hours after it first appears, the non-transparent portion of the anvil clouds observed in this study reached their greatest horizontal extent, defined above as the mature stage. After reaching the mature stage the anvil cloud began to dissipate, revealing surface features and lower clouds beneath it in the visible imagery. A record was made of the maximum distance from the non-transparent edge of the mature anvil cloud to the location where the parent cluster of thunderstorms originated, along with the coordinates of the originating location and the direction from the originating point to the edge of the anvil.

2.1.2 Radiosonde Data

Atmospheric wind speeds and directions were determined for each anvil by using data from the nearest radiosonde station, provided it preceded the anvil observation by less than 12 hours. Wind speed and direction observations at all reported pressure levels were linearly averaged for the upper-tropospheric layer from 300 to 150 mb, and the lower-tropospheric layer from 900 to 500 mb. The dew point depression in the upper-layer was also averaged from the same radiosonde data and recorded.

2.2 Results from Anvils Observed in May – July 2001

The life cycles of 167 anvil clouds were monitored on 50 anvil case days during the months of May – July 2001. Dr. Short recorded anvil length at maturity, anvil orientation with respect to the parent thunderstorm complex, wind speed/direction in the lower- and upper-troposphere and dew point depression in the upper-troposphere for each anvil. Daily averages of all variables were computed for each case day and subjected to the statistical analyses described below and in Short et al. (2002).

2.2.1 Anvil Direction and Upper-Tropospheric Wind Direction

The direction of propagation of thunderstorm anvil clouds was found to be highly correlated with the wind direction in the upper-tropospheric layer from 300 to 150 mb. Figure 3a shows a scatter diagram of the layer-averaged upper-tropospheric wind direction and anvil orientation for the 50 case days described above. The diagonal lines indicate the 1:1 line and an envelope of +/- 60 degrees. The correlation coefficient between the two variables is 0.97. The layer-averaged winds were from the southwest through northwest for most of the case days with a few days showing winds with an easterly component. The average upper-level wind direction for the 50 case days was 345°, only one degree greater than the average anvil direction. This indicates that the upper-level wind direction gives a nearly unbiased indication of anvil orientation. The vast majority of points lie close to the 1:1 diagonal with a few outliers showing discrepancies of more than 60° between the anvil orientation and the upper-level wind direction.

Figure 3b shows the direction difference between the anvil orientation and wind direction as a function of upper tropospheric wind speed. Differences are greatest for lower wind speeds. The standard deviation of differences is about 25° overall, but only about 15° for wind speed greater than 20 kts. The dashed lines indicate +/- one standard deviation trends, estimated by a 2nd-order polynomial fit to difference statistics for the three intervals from 0-20, 20-40, and 40-60 kts. This result indicates that anvil orientations are more highly correlated with wind direction as the wind speed increases and provides a useful first-guess value for the width of the threat sector referred to above and described in detail in section 3.1.

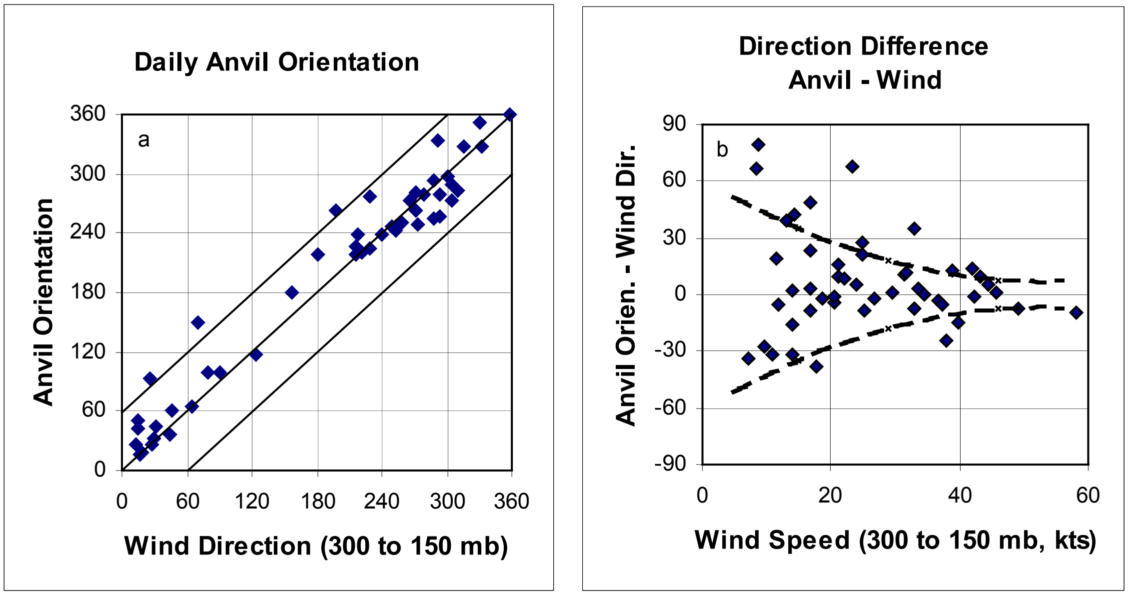


Figure 3. Daily anvil orientation versus wind direction in panel (a) and deviation of anvil orientation from wind direction versus wind speed in panel (b). Note that the deviations are largest at the lowest wind speeds. The dashed lines in (b) indicate +/- one standard deviation trends, estimated from difference statistics for the three intervals from 0-20, 20-40, and 40-60 kts.

2.2.2 Anvil Transport Lifetime and Upper-Tropospheric Wind Speed

Figure 4a shows a scatter diagram of daily averages of layer-averaged wind speed in the upper-troposphere versus anvil distance. A linear regression between the two variables gives an intercept of 21 nmi and a slope of 1.9 nmi/kt. With a correlation coefficient of 0.85 the regression relation explains 73% of the variance of anvil distance by the wind speed. The non-zero intercept indicates that anvil clouds can be expected to reach a scale of about 21 nmi, centered on their parent thunderstorm complex, when the upper-level wind speed is near zero, due to the inertia and divergence of the convective updrafts and their load of hydrometeors.

Figure 4b shows a scatter diagram of wind speed versus anvil length minus the 21 nmi offset mentioned previously. The solid sloping lines indicate time scales that are consistent with the wind speed and anvil distances. For example, a length of 100 nmi and a speed of 50 kts indicate a time scale of 2 hours. The timescale is referred to as an effective transport lifetime, indicating the approximate time it took the anvil cloud to reach its maximum extent at maturity. The average effective transport lifetime is 1.9 hours with a standard deviation of 0.58 hours.

The results shown in Figure 4 are consistent with the 45 WS pilot study based on 17 anvil case days during 1999 and 2000 (Lambert 2000). That study included days during the Florida cool season, November through March, with wind speeds as high as 72 kts, in addition to days during the Florida warm season, May through September. An effective average transport lifetime of 2.2 hours was derived from that database.

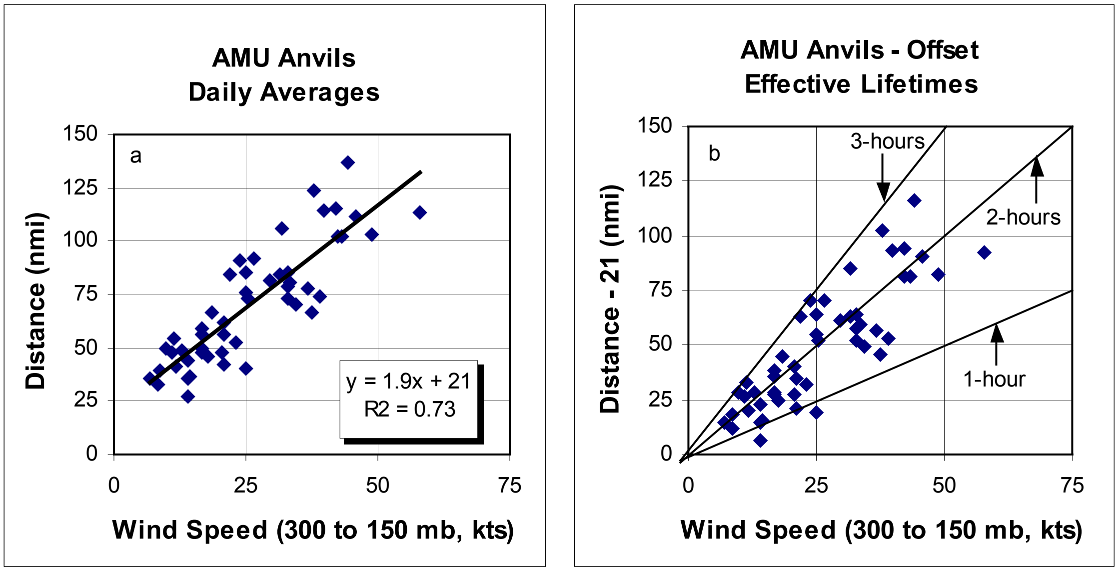


Figure 4. Daily averages of wind speed versus anvil distance in panel (a) and daily averages of wind speed versus anvil distance minus offset in panel (b). The 21 nm offset used in (b) was determined from the linear regression in (a). The sloping lines in (b) denote effective transport lifetimes, calculated from the ratio of distance-offset to wind speed.

2.2.3 Lower-Tropospheric Wind Speed and Direction

Visual inspection of satellite imagery indicated a clear influence of the lower-tropospheric winds on the motion of convective cells and thunderstorms during their developing stages. The average angle between the lower-level winds (900 to 500 mb) and the upper-level winds (300 to 150 mb) was computed at 60° on the 50 anvil case days, with a clockwise rotation with increasing height. However, once an anvil had formed and began to expand, its motion was clearly in accord with the upper-level winds. Therefore, it was concluded that the lower-tropospheric wind information does provide important clues to the motion of developing convective cells, but does not provide additional information on the subsequent propagation and lifetime of thunderstorm anvil clouds that can be incorporated into an anvil forecasting technique.

2.2.4 Upper-Tropospheric Humidity

Figure 5 shows a scatter diagram of dew point depression versus transport lifetime for the 50 anvil case days documented in the present study. A linear regression gives a correlation coefficient of 0.03 and a slope near zero, indicating no useful relationship between the variables. The cluster of data points in Figure 5 with values between 6 and 8ºC is similar to a cluster in the pilot study. However, the data points in the present study fill out the remainder of the space in a random fashion, whereas the pilot study had two outliers with large dew point depressions and short transport lifetimes.

The 45 WS pilot study indicated a significant correlation between anvil transport lifetime and the dew point depression in the anvil layer. The database included 17 anvil days throughout the seasonal cycle in 1999 and 2000. The small number of sample points used for this preliminary study may have been responsible for the appearance of longer lived anvils in more humid air.

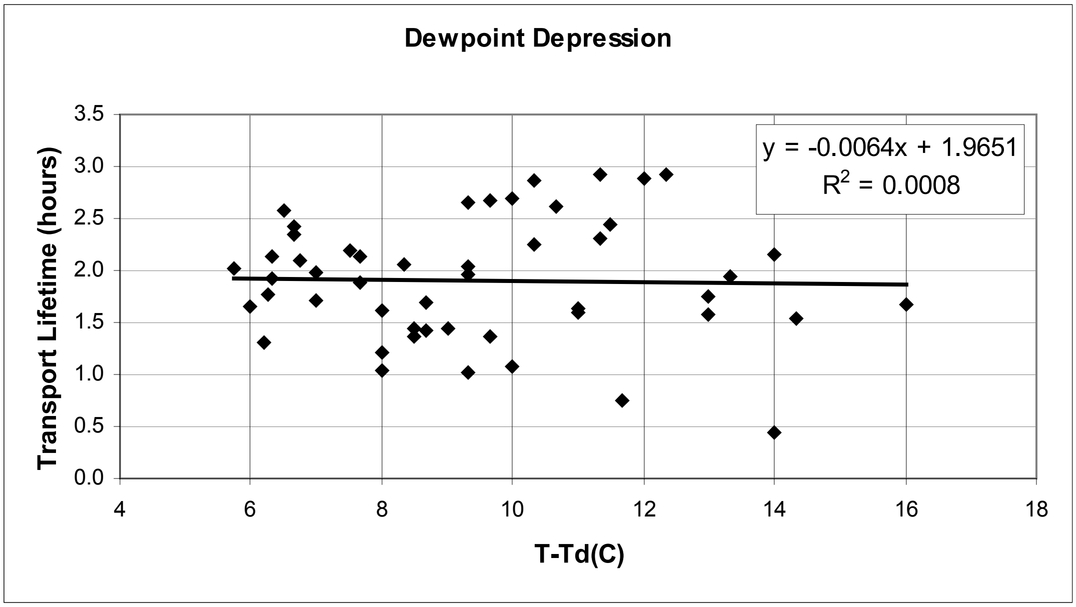


Figure 5. Daily averages of dew point depression versus transport lifetime for the 50 anvil case days observed during May through July 2001. Transport lifetimes were derived from the analysis shown in Figure 4b. The solid line was determined by linear regression.

2.3 Upper-Tropospheric Climatology

Empirical evidence presented in section 2.2 shows that the propagation characteristics of thunderstorm anvil clouds observed over Florida and its coastal waters during the months of May through July 2001 are highly correlated with the wind speed and direction in the layer between 300 and 150 mb. Observations of wind, temperature and humidity information are routinely reported in radiosonde observations at the mandatory level of 300 mb, 250 mb, 200 mb, 175 mb and 150 mb, assuring a consistent assessment of conditions within the anvil cloud layer. Data at intermediate pressure levels are only reported when significant deviations from trends in the mandatory levels are observed.

The 300 mb and 150 mb pressure surfaces encompass a layer about 15 000 ft thick, between about 31 000 ft and 46 000 ft altitude (as shown in Figure 6). The annual variability of the height of the 300 and 150 mb surfaces shown in Figure 6 was derived from a 20-year climatology of upper-air observations developed by the Range Commander's Council Meteorology Group for the CCAFS radiosonde station, XMR. The data are available on the following website: http://www.edwards.af.mil/weather/rcc.htm

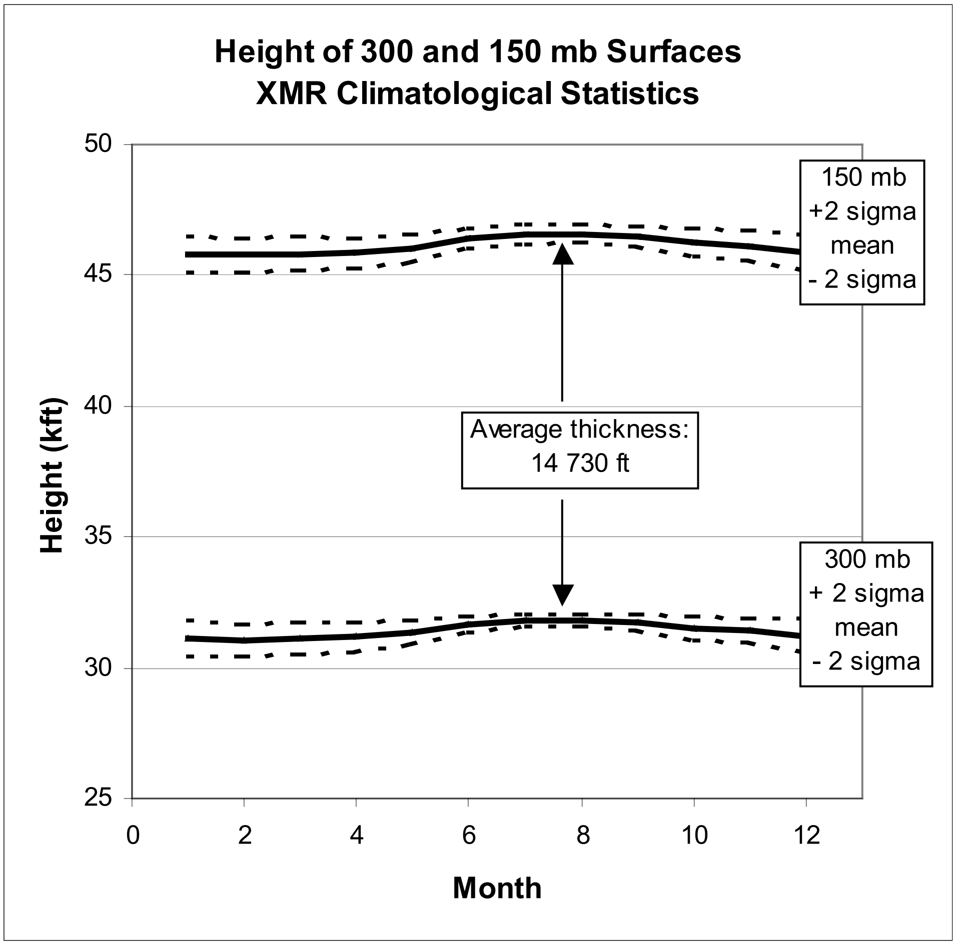


Figure 6. Annual cycle of the height of the 300 mb and 150 mb surfaces from a 20-year climatology of observations from the Cape Canaveral radiosonde station, XMR. The period of record for the climatology is January 1973 to December 1992. Solid lines indicate monthly average values. The dashed lines indicate the statistical variability, +/- two standard deviations.

An additional factor to consider in determining the location of the anvil cloud layer is the height of the tropopause, the boundary between the troposphere and the stable stratosphere above. Vigorous convective updrafts rise to the tropopause, transporting the hydrometeor supply that creates anvil clouds. Only the strongest updrafts can overshoot the tropopause and only for a brief time. The tops of anvil clouds are correspondingly found at or below the tropopause.

Figure 7 shows the annual variability in the pressure at the height of tropopause as derived from the 20-year climatology of observations from XMR. Values on the y-axis are plotted in reverse order to indicate increasing altitude with decreasing pressure. The mean pressure at the tropopause is about 150 mb, but varies from about 160 mb in spring to about 125 mb in early fall. The pressure at the tropopause is least variable during summer, being found between 155 mb and 110 mb more than 80% of the time. During winter the pressure at the tropopause is more variable, occasionally greater than 300 mb.

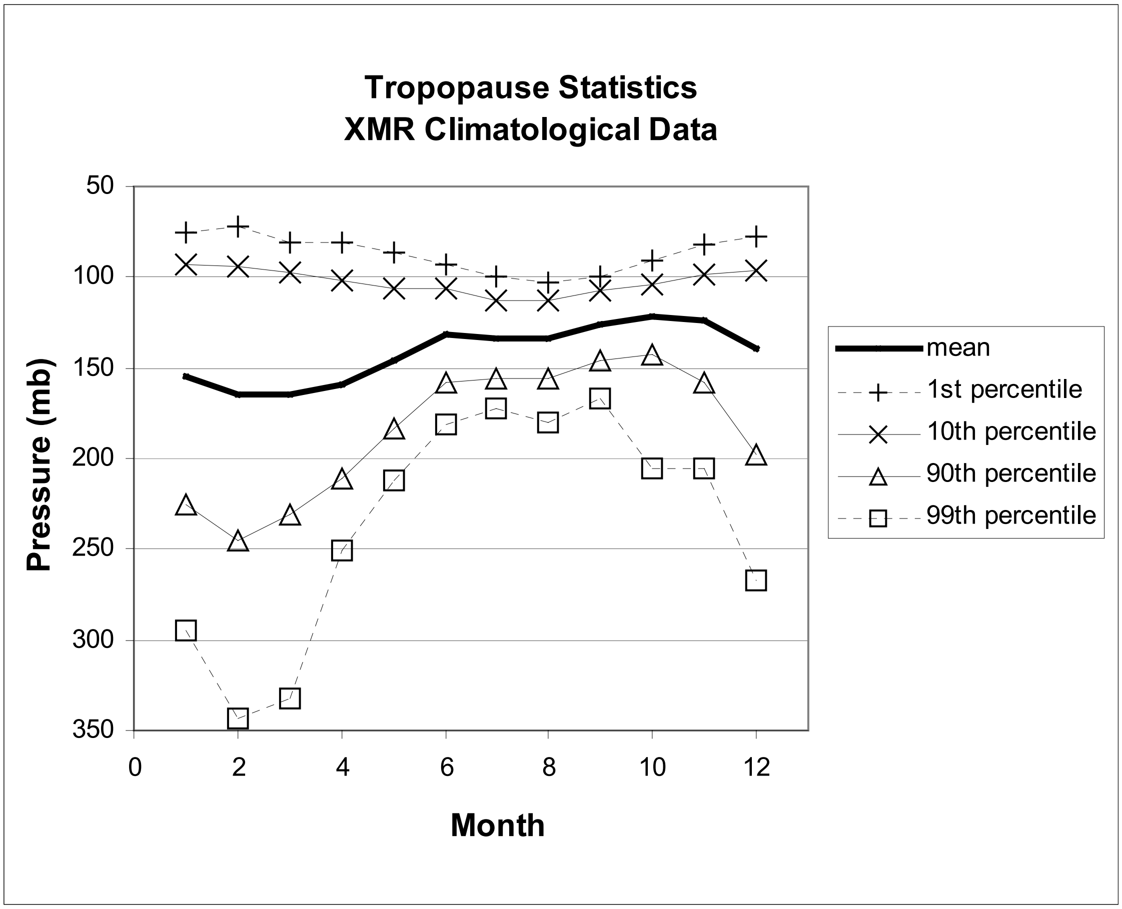


Figure 7. Annual cycle of pressure variability at the tropopause over XMR. The period of record for the climatology is January 1973 to December 1992. The solid thick line indicates monthly means. The solid thin lines indicate the 10th and 90th percentiles above and below the mean, respectively. The dashed thin lines indicate the 1st and 99th percentiles above and below the mean, respectively.

The climatology of tropopause pressure shows that 150 mb is a good first-guess for the height of the tropopause and the upper boundary of the anvil cloud layer during the warm season, May through September. However, during other times of the year the tropopause may be considerably lower (its pressure considerably higher) and a corresponding adjustment may be required to improve the accuracy of a year-round anvil-forecasting tool.

3. Graphical Forecast Tool

Visual and graphical products are mainstays of weather forecasting, aiding comprehension of the vast time and space domains encompassed by weather events. With practice and experience, visual products can be quickly interpreted, facilitating an integrated understanding of complex and evolving weather scenarios.

The anvil-forecasting tool described below is designed to automatically draw an anvil threat sector on top of an image (satellite or radar composite) on a MIDDS display. In the pre-convective environment the threat sector will alert the forecaster to the specific area where anvils from developing thunderstorms could threaten the launch area within the timeframe of the next several hours.

3.1 Extrapolation/Advection Forecast Tool

The observational studies documented above and in the Phase I report (Lambert 2000) indicate that the motion of anvil clouds is highly correlated with the speed and direction of upper-level winds. As a result a short-term anvil-forecasting tool can be formulated to extrapolate future positions of anvil clouds as they are advected by the upper-level wind field. By combining data into easily understood information, graphical products help reduce information overload for the meteorologist.

Figure 8 shows a schematic representation of an anvil threat sector. The following threat sector properties are consistent with the propagation and lifetime characteristics of thunderstorm anvil clouds observed over Florida and its coastal waters:

- 20 nmi standoff circle,
- 30 degree sector width,
- Orientation given by 300 to 150 mb average wind direction,
- 1-, 2- and 3- hour arcs in upwind direction, and
- Arc distances given by 300 to 150 mb average wind speed.

The AMU developed a prototype short-term anvil-forecasting tool for implementation on MIDDS. The tool, activated by a one line McIDAS command, is written in Beginner's All-purpose Symbolic Instruction Code (BASIC) for McIDAS (McBASI) and runs a McBASI script. Appendix A contains a flow chart of the script, which automatically computes the average wind speed and direction in the layer between 300 and 150 mb from the latest sounding for a user designated station.

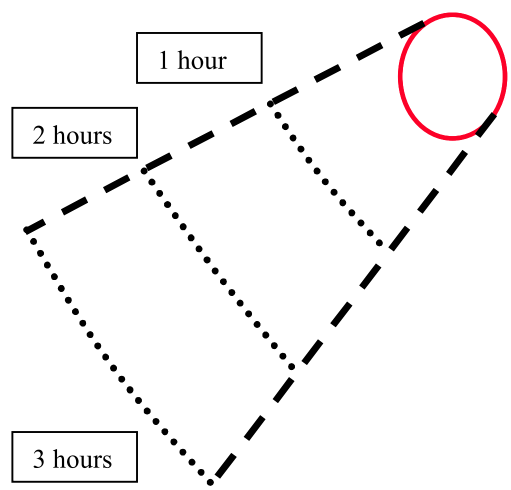


Figure 8. Schematic representation of an anvil threat sector. The sector is 30º in width, extending toward the southwest from a 20 nmi circle centered on the station of interest. Arcs are located upstream at distances consistent with 1-, 2- and 3-hour transport times by the upper-level winds.

The tool is meant to be used as follows: If thunderstorms are forecast to occur within the threat sector, their anvil clouds will likely move over the KSC/CCAFS within the time interval shown by the arcs in Figure 8.

Figure 9 shows an example of the appearance of the anvil forecast tool when overlaid on a visible satellite image. Space Launch Complex 39A was selected as the center point. The anvil threat corridor was determined from upper-level wind data observed at 1500 Coordinated Universal Time (UTC), 1100 Eastern Daylight Time (EDT), in the pre-convective environment. The visible satellite image is for 1915 UTC (1515 EDT), just as convective activity begins to form in Central Florida. The threat corridor indicates that once anvil clouds are formed they will be transported over the KSC/CCAFS area in less than 2 hours.

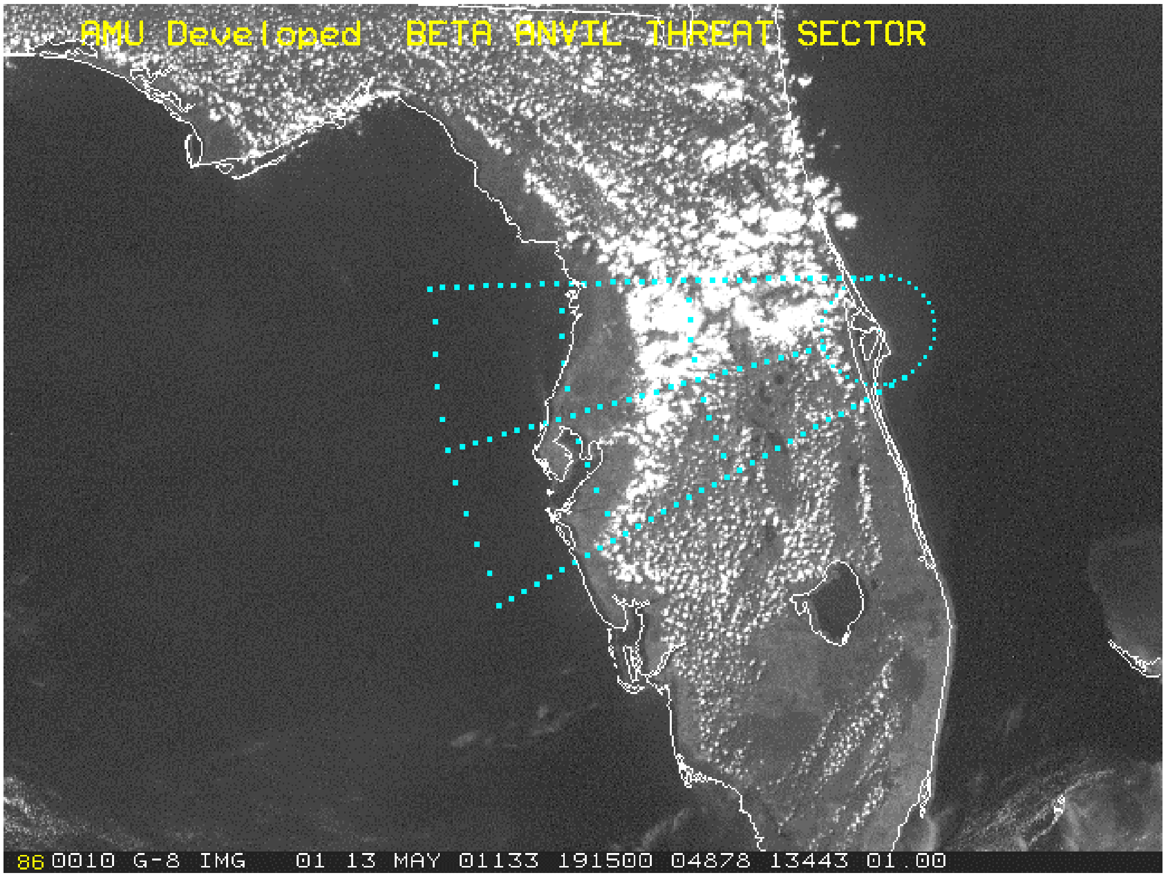


Figure 9. An example of the anvil forecast graphic overlaid on a visible satellite image of the Florida peninsula. The anvil threat corridor was computed from radiosonde data observed at XMR at 1500 UTC (1100 EDT), 13 May 2001, prior to the onset of convective activity. The satellite image was observed at 1915 UTC (1732 local time) just after the onset of convection in central Florida.

Figure 10 shows the anvil forecast tool overlaid on a visible satellite image that was observed at 2132 UTC, 2 hours and 17 minutes after the satellite image shown in Fig. 9. Space Launch Complex 39A was selected as the center point, and the anvil threat corridor was determined from upper-level wind data observed at 1500 UTC in the pre-convective environment. Narrow thunderstorm anvil clouds extend from central Florida to the space launch and landing facilities on KSC and CCAFS and beyond. The anvil clouds were generated around 1930 UTC (1430 EDT) by thunderstorm activity over central Florida and transported 90 nautical miles east-northeastward within 2 hours, as predicted by the anvil forecast tool.

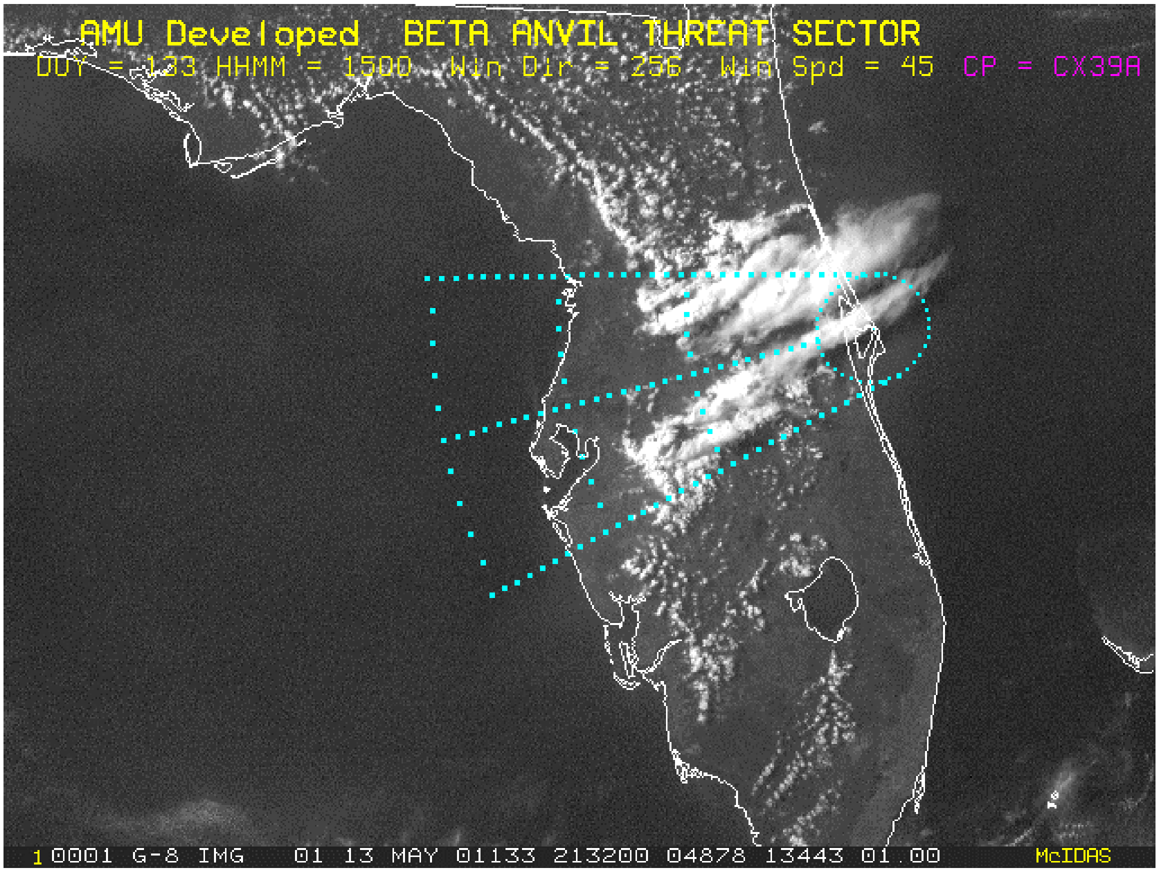


Figure 10. As in figure 9, but for 2132 UTC (1732 EDT). Thunderstorms that formed within the graphical threat sector produced anvil clouds that moved over the KSC/CCAFS area.

3.2 Implementation

The prototype anvil-forecast tool was written as a McBASI script that runs on MIDDS. It has been tested on the MIDDS in the AMU and by SMG on their MIDDS display system. The script was designed so that it can be implemented and executed on the operational MIDDS in the RWO without impacting the operational configuration of the system. The script was designed so that it does not generate lingering McIDAS processes on the system, thereby requiring a minimum of operator attention.

3.3 Training

The AMU will provide one-on-one training for LWOs and SMG forecasters to familiarize them with use of the anvil forecast tool on MIDDS. In addition, the McBASI script contains a "HELP" section that can be accessed by the operator by issuing the following command line:

HELP AMUANVILWND

Table 1 lists the McIDAS command line options for executing the anvil forecast tool on MIDDS. The command is "AMUANVILWND" followed by as many as three optional fields, indicated as variable one, variable two and variable three. The default command with no optional fields centers the threat corridor on SLC 39A and uses upper-air data from XMR. The user can select other center point locations in the KSC/CCAFS area by entering one of the next ten options indicated under the "Variable One" column in Table 1. The threat corridor for the first eleven commands in Table 1 will be based on upper-air data from XMR.

The user can center the threat corridor on another upper-air station by specifying "OTHER" as variable one and by entering the five-digit identifier as variable two. In this case the user can specify up to three other stations, using variable three to indicate the order of the text labels that give the station ID, date/time of the radiosonde data and derived wind speed and direction. The "ASK" option for variable one allows the user to specify latitude/longitude coordinates and wind speed/direction.

Table 1. McIDAS command line options for running the anvil-forecasting tool.

McIDAS Command	Variable One	Variable Two	Variable Three	Center Point	Text Label
AMUANVILWND	N/A	N/A	N/A	Default: SLC 39A	Line 0
AMUANVILWND CX17	CX17	N/A	N/A	SLC CX17	"
AMUANVILWND CX 17A	CX17A	N/A	N/A	SLC CX17A	"
AMUANVILWND CX36	CX36	N/A	N/A	SLC CX36	"
AMUANVILWND CX39	CX39	N/A	N/A	SLC CX39	"
AMUANVILWND CX39A	CX39A	N/A	N/A	SLC CX39A	"
AMUANVILWND CX39B	CX39B	N/A	N/A	SLC CX39B	"
AMUANVILWND CX40	CX40	N/A	N/A	SLC CX40	"
AMUANVILWND CX41	CX41	N/A	N/A	SLC CX41	"
AMUANVILWND SLF	SLF	N/A	N/A	SLF	"
AMUANVILWND MLB	MLB	N/A	N/A	MLB	"
AMUANVILWND OTHER NNNNN L	OTHER	NNNNN	L=1, 2, or 3	Station NNNNN	Line L
AMUANVILWND ASK	ASK	N/A	N/A	User Specified Lat/Lon, Speed/Dir.	Line 0

4. Summary and Recommendations

The 45 WS LWOs and SMG forecasters have identified anvil forecasting as one of their most challenging tasks when predicting the probability of lightning LCC and Space Shuttle FR violations. Electrified thunderstorm anvil clouds extend the threat of natural and triggered lightning to space launch and landing operations far beyond the immediate vicinity of thunderstorm cells. The deep convective updrafts of thunderstorms transport water vapor, super-cooled water droplets and ice crystals into the upper-troposphere, forming anvil clouds, which are then carried downstream by the prevailing high-level winds. Electrified anvil clouds have been observed over the space launch and landing facilities of KSC and CCAFS emanating from thunderstorm activity more than 100 nmi distant.

Phase I of this task established the technical feasibility of developing an objective, observations-based tool for short-range anvil forecasting. The AMU was subsequently tasked by its customers to develop short-term anvil forecasting tools to improve predictions of the threat of triggered lightning to space launch and landing vehicles. This Phase II effort began with a data collection and analysis effort to determine statistical parameters of the forecast tool. This report documents the development and implementation of a short-range anvil forecast tool that has been designed by the AMU for operational use on MIDDS by 45 WS LWOs and SMG forecasters.

4.1 Observation-Based Forecast Tool

The AMU developed a graphical short-range, observations-based, anvil-forecast tool that gives the user a quick look at an upstream corridor from which anvil clouds could threaten the KSC/CCAFS area within a few hours. The tool includes several options that allow the user to depict anvil threat corridors at locations of their choosing. The anvil forecast tool was designed for operational use on MIDDS in the RWO by 45 WS LWOs and forecasters at SMG. It has been developed and tested on the AMU MIDDS and further tested on the SMG MIDDS with success. The tool automatically accesses routine upper-air observations, computing the average wind speed and direction in the anvil layer. It then uses the speed and direction information to overlay an anvil threat corridor on a MIDDS image. The tool is invoked by a one-line McIDAS command on MIDDS and contains a help file invoked by the standard McIDAS HELP command.

4.2 Recommendations

The AMU recommends implementation of the short-range anvil-forecast described herein on the operational MIDDS in the RWO.

Further development of the observations-based anvil-forecast tool may include the following:

- Vary the pressure interval over which the wind speed and direction are computed from radiosonde observations. This option may be needed to take into account variations in the height of the tropopause, especially during the cool season, November through March.
- Use upper-level wind speed and direction information from the KSC 50-MHz Doppler radar wind profiler.

Further development of a model-based anvil-forecast tool may include the following:

- Use gridded upper-level wind data from the 3- to 12-hour RUC forecast.
- Incorporate information from the "VVSTORM" experimental product to determine if convective activity is forecast within the threat sector. (See the following website: http://www.awc-kc.noaa.gov/awc/vvstorm.html)

It should be noted that recent and future field experiments dedicated to determining electrical and microphysical characteristics of thunderstorm anvil clouds may provide additional information that may be useful for improving the short-term anvil-forecast tool within the next year or two. For example, the Airborne Field Mill program has obtained in-flight data on the rate of charge dissipation within anvil clouds near KSC (Merceret and Christian 2000). The Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL – FACE), scheduled for the summer of 2002, is a regional study dedicated to improved observations and models of anvil clouds. See the following website for detailed information on CRYSTAL – FACE: http://cloud1.arc.nasa.gov/crystalface/index.html

References

Detwiler, A. and A. J. Heymsfield, 1987: Air motion characteristics in the anvil of a severe thunderstorm during CCOPE. *J. Atmos. Sci.*, **44**, 1899-1911.

Garner, T., R. Lafosse, D. G. Bellue, and E. Priselac, 1997: Problems associated with identifying, observing, and forecasting detached thunderstorm anvils for Space Shuttle operations. Preprints, *7th Conference on Aviation, Range, and Aerospace Meteorology*, Long Beach, CA, Amer. Meteor. Soc., 302-306.

Krider, E. P., H. C. Koons, R. L. Walterscheid, W. D. Rust, and J. C. Willett, 1999: Natural and Triggered Lightning Launch Commit Criteria (LCC). Prepared by The Aerospace Corporation, El Segundo CA 90245, Aerospace Report TR-99(1413)-1; Prepared for Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles AFB, CA 90245, SMC Report SMC-TR-99-20. 15 pp.

Lambert, W. C., 2000: Improved anvil forecasting: Phase I Final Report. NASA Contractor Report CR-2000-208573, Kennedy Space Center, FL, 24 pp [Available from ENSCO, Inc., 1980 N. Atlantic Ave., Suite 230, Cocoa Beach, FL, 32931].

Marshall, T. C., W. D. Rust, W. P. Winn, and K. E. Gilbert, 1989: Electrical structure in two thunderstorm anvil clouds. *J. Geophys. Res.*, **94**, 2171-2181.

Merceret, F.J. and H. Christian, 2000: KSC ABFM 2000 - A Field Program to Facilitate Safe Relaxation of the Lightning Launch Commit Criteria for the American Space Program, Preprints, *9th AMS Conference on Aviation and Range Meteorology*, Orlando, FL, Amer. Meteor. Soc., 447-449.

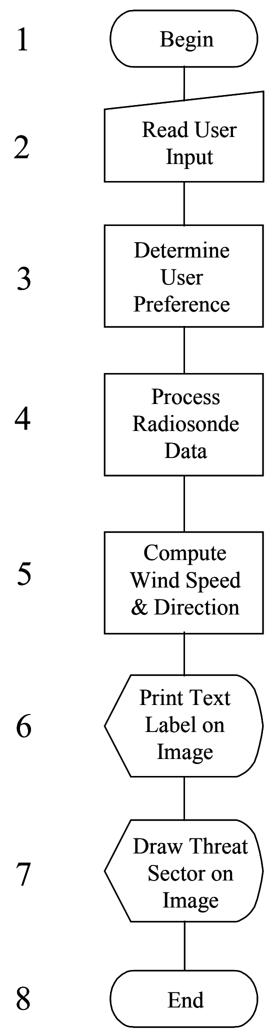
Roeder, W. P., J. E. Sardonia, S. C. Jacobs, M. S. Hinson, D. E. Harms, and J. T. Madura, 1999: Avoiding triggered lightning threat to space launch from the Eastern Range/Kennedy Space Center, Preprints, *8th Conference on Aviation, Range, and Aerospace Meteorology*, Dallas, TX, Amer. Meteor. Soc., 120-124.

Short, D. A., J. E. Sardonia, W. C. Lambert, and M. M. Wheeler, 2002: Propagation and lifetime characteristics of thunderstorm anvil clouds over Florida. Preprints, *18th Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography and Hydrology*. Orlando, FL, Amer. Meteor. Soc., 19-21.

APPENDIX A

Flowchart

The anvil forecast McBASI script performs a sequence of eight steps when invoked on MIDDS by any one of the command lines shown in Table 1. The eight steps are as follows:



NOTICE