Improved Anvil Forecasting:
Phase I Final Report

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Executive Summary

The 45th Weather Squadron (45 WS) Launch Weather Officers (LWO) and the Spaceflight Meteorology Group (SMG) forecasters have identified anvil forecasting as one of the most difficult tasks when attempting to predict Launch Commit Criteria (LCC) and Space Shuttle Flight Rules (FR) violations. However, only simplistic and unrefined forecast tools are available to help determine whether anvils will form or the length and thickness of anvils that do form. The purpose of the task is to determine the technical feasibility of creating anvil-forecasting tools.

Work on this study was separated into three steps: a literature search, forecaster discussions, and determination of the feasibility to continue with product development. The literature search was meant to reveal any previous work done on this topic. Forecaster discussions were necessary to provide insight to the details of the forecasting problem and to gather ideas on how an anvil-forecasting technique could be developed. Finally, all the information was assimilated and a determination of the feasibility to develop an anvil forecasting technique was made.

The literature search step revealed no existing anvil-forecasting techniques. However, it is important to mention that there appears to be growing interest in anvils in recent years. If the interest in anvils continues to grow, more information will be available to aid in developing a reliable anvil-forecasting tool. The forecaster discussion step revealed an array of methods on how forecasting is currently done and how better techniques could be developed. Operational forecasters have ideas based on sound meteorological principles and a great deal of personal experience in forecasting and analyzing anvils. A technique proposed by one of the LWO's that uses observational data, although still in the development stage, shows 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. A modeling study may also help to define what data are needed to develop an observations-based anvil-forecasting tool.

Based on the information gathered in the discussions with the forecasters, the conclusion of this report is that it is technically feasible at this time to develop an anvil forecasting technique that will significantly contribute to the confidence in anvil forecasts. The forecasters suggested an observations-based study and two types of modeling studies. The advantages, disadvantages, and likelihood of success of each as well as the AMU Phase II recommendation are given in this report.

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List of Acronyms

Term	Description
45 WS	45th Weather Squadron
AC	Atlas/Centaur
AMS	American Meteorological Society
AMU	Applied Meteorology Unit
AOA	Abort Once Around
ARPS	Advanced Regional Prediction System
AVN	Aviation
CCAFS	Cape Canaveral Air Force Station
DOTA	Detached Opaque Thunderstorm Anvil
DD	Dew Point Depression
DRWP	Doppler Radar Wind Profiler
EOM	End of Mission
FR	Flight Rules
GOES	Geostationary Operational Environmental Satellite
HIRLAM	High-Resolution Limited Area Model
IR	GOES Infrared satellite data
KSC	Kennedy Space Center
LAP	Lightning Advisory Panel
LCC	Launch Commit Criteria
LPLWS	Launch Pad Lightning Warning System
LWO	Launch Weather Officer
MCS	Mesoscale Convective System
MIDDS	Meteorological Interactive Data Display System
MGA	Meteorological and Geoastrophysical Abstracts
MLB	Melbourne, Florida
MRF	Medium Range Forecast
NGM	Nested Grid Model
NWS	National Weather Service
NWS MLB	NWS in Melbourne, Florida
P(DOTA)	Probability of Detached Opaque Thunderstorm Anvils
P(TS)	Probability of Thunderstorms
PLS	Planned Landing Site
RAMS	Regional Atmospheric Modeling System
RH	Relative Humidity
ROCC	Range Operations Control Center

RTLS	Return to Launch Site
RUC	Rapid Update Cycle
SLF	Shuttle Landing Facility
SMG	Spaceflight Meteorology Group
TAL	Trans-oceanic Abort Landing
TS	Thunderstorm
VIS	VISible
WSR-88D	Weather Surveillance Radar-1988 Doppler
XMR	CCAFS weather station 3-letter identifier

1. Introduction

The 45th Weather Squadron (45 WS) Launch Weather Officers (LWO) have identified anvil forecasting as one of the most difficult tasks when attempting to predict the triggered lightning Launch Commit Criteria (LCC) violation probability. The Spaceflight Meteorology Group (SMG) forecasters reiterate this difficulty when evaluating Space Shuttle Flight Rules (FR). However, there are only simple and unrefined forecast schemes in existence to help determine whether anvils will form from existing thunderstorms or the length and thickness of anvils that do form.

The purpose of the task is to identify or develop an objective technique to forecast anvil features to aid in the prediction of lightning LCCs and FRs. However, uncertainties in the possibility of developing an anvil-forecasting tool prompted the decision to separate the task into two phases. Phase I consists of a study to determine the technical feasibility of creating anvil-forecasting tools. Favorable results from the Phase I study mean that the task could continue with product development in Phase II. This report describes the results from Phase I.

In determining the possibility of developing an anvil forecasting technique to aid in evaluating LCC and FRs, it is important to understand the motivation for their creation. This is discussed in Section 1.1. The task methodology is outlined in Section 1.2.

1.1. Anvil Electrification Hazard

An anvil forms when the air and hydrometeors in a thunderstorm updraft reach a stable layer in the upper troposphere and spread out horizontally. The anvil will generally develop downstream of the parent storm in the airflow at the stable layer. But it can also spread upstream and laterally to the flow depending on the strength of the storm updraft and the strength of the horizontal wind at the stable layer.

There have been few direct observations of the electrical structure in anvils (Byrne et al. 1989, Marshall et al. 1989). It is generally believed that the process of anvil formation is fundamental in how the anvil acquires its electrical charge structure. The ice crystals that are forced into the anvil from the updraft carry the positive charge typically found in the upper region of a thunderstorm. Negative charges then move toward this positive charge and form negatively charged layers (Marshall et al. 1989) above and below the anvil. These layers are called screening layers because they shield the atmosphere outside the anvil from the effects of the positive charge within (Marshall et al. 1989). The theoretical charge structure of an anvil is, therefore, a positively charged interior surrounded by a negatively charged exterior layer. There is some evidence from Byrne et al. (1989) that the charge structure in severe storm anvils may be more complex, but the basic structure found was similar to the theoretical structure described above. 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 above the network.

If the flight path of a space vehicle carries it through such an electrified environment, the disturbance could cause a phenomenon known as triggered lightning. This lightning could severely disable the electronics on board the vehicle causing it to go off course or self-destruct. Such an incident occurred in March 1987 with the Atlas/Centaur (AC) 67 vehicle (Christian et al. 1989). The vehicle was struck by triggered lightning 48 seconds into flight causing the electronics on board to issue an incorrect yaw command. This resulted in an excessive angle of attack, large vehicle loads, and subsequent breakup of AC 67. The field mill network indicated that the overhead clouds were electrified, and satellite images indicated an anvil was over the Cape. It was not concluded that the triggered lightning came from the anvil, but it is clear that electrified clouds, be they anvil or not, can create a dangerous environment for space vehicles.

The 45 WS and SMG have LCCs and FRs to minimize space vehicle exposure to conditions conducive to the creation of triggered lightning. The LCCs and FRs are described in Appendix A.

1.2. Task Methodology

The work on Phase I was separated into three steps: literature search, forecaster discussions, and determination of the feasibility to continue with Phase II. The literature search was done to reveal any previous work on this topic. Forecaster discussions were necessary to help determine the details of the forecasting problem and to gather ideas on how such a technique could be developed. In the final step all the information was assimilated in order to make a final determination of the feasibility of developing an anvil forecasting technique. The next three subsections describe each of the steps in more detail.

1.2.1.   Literature Search

The task began with a search for all applicable literature on the topic of anvils in general. This part of the task was instrumental in determining if anvil-forecasting techniques and tools already exist or if they must be developed from scratch. Articles that specifically discussed anvil forecasting did not exist. Research experiments to analyze anvils have taken place, but their results are not useful for developing an anvil-forecasting tool. However, there appears to be a growing interest in anvils within the research community, and the results from future studies could be helpful during a product development phase.

1.2.2.   Forecaster Discussions

These discussions provided insight to the details of the forecasting problem and were invaluable in determining if a forecasting technique could be developed. The forecasters were first asked how the forecast is currently made. A list of data sources and specific variables that the forecasters think are important in forecasting anvil was compiled. The data sources include model output, satellite images, radar data, and upper-air soundings. Forecasters were then asked for ideas of products or techniques that would be helpful in making this forecast. Any and all information and opinions were accepted and considered. It was these discussions that provided the most important information regarding the development of anvil forecasting techniques and tools.

1.2.3.   Determine Technical Feasibility

In the final step, all information gathered from the literature and the forecasters was assimilated to determine the feasibility of continuing with Phase II. Since no former studies on anvil forecasting were found in the literature, a technique must be developed from scratch. Input gathered from the forecaster discussions will be absolutely necessary, therefore, to develop an anvil forecasting method.

Technical feasibility is the only thing determined in this task. This report provides all options available as found through the forecaster discussions. A detailed work plan on the specific steps in developing a forecasting method will be drawn up only if the Applied Meteorology Unit (AMU) is tasked with continuing a subsequent phase.

2. Literature Search

Both the Meteorological and Geoastrophysical Abstracts (MGA) and the American Meteorological Society (AMS) online journal abstract search capability were used to find articles related to anvil formation, anvil electrification, and anvil forecasting. No articles were found in which a tested and proven anvil forecasting technique was described. Brief descriptions of these articles are given in Appendix B.

The articles found can be broadly separated into the two categories of observational and modeling studies. Several studies were concerned with the effect anvil microphysical properties have on incoming solar and outgoing terrestrial radiation. These studies were done with the eventual goal of developing anvil microphysical parameterization schemes for global climate models. Two articles examined anvil electrification, and one article proposed that ingested anvil particles could be the cause of aircraft engine problems. Of the three modeling studies, two attempted unsuccessfully to model the microphysics and location of anvils and the other proposed a cirrus parameterization scheme for more accurate representation of cirrus and anvils in models. Most of the studies in both categories concluded that more operational and modeling studies of anvils and anvil parameters must be done to fully understand their behavior.

Although no anvil forecasting techniques were found in the literature, it is important to mention that there appears to be growing interest in anvil parameters in recent years. Of the 17 articles cited in the Reference section, 12 are dated 1989 or later. If the interest in anvils grows and more articles are written, more information will be available to aid in developing a reliable anvil-forecasting tool. Likewise, knowledge of how anvils form will naturally come from developing such a tool, and this knowledge would contribute to the general understanding of anvils in the scientific community.

3. Forecaster Discussions

Discussions were held with forecasters from the 45 WS, SMG, and the NWS in Melbourne, Florida (MLB). They described how forecasts for anvils are currently made and offered ideas on how a forecasting technique could be developed.

Similarities exist in the way all three groups currently make anvil forecasts. In the day or days prior to an operation they use model forecasts of thunderstorm location/motion and upper-level wind speed/direction to help determine if anvils will be over the area. On the day of the operation, rawinsonde data are used to analyze upper-level winds and RH. Satellite and radar data are used for locating thunderstorms and anvils and determining their direction and speed of movement. Finally, as the time for the operation approaches, human observations of an anvil over the area are taken from the ground and/or aircraft to deduce anvil thickness and transparency.

Although they are commonly used, all forecasters agree that these procedures are not adequate for forecasting anvils and an objective method is needed. Currently used and proposed methods from each individual group are described in the following sections. It is important to note that none of these methods, either current or proposed, have been tested or verified to be accurate.

3.1. 45th Weather Squadron

During the 1999 warm season, Mr. Jim Sardonia, the Atlas LWO, collected and analyzed a small data set to see if any correlations existed between the data and anvil formation and growth. The data set included Geostationary Orbiting Environmental Satellite (GOES) visible (VIS) data, GOES sounding data, forecast data from the Medium Range Forecast (MRF), Rapid Update Cycle (RUC), and the 32-km Eta models, and CCAFS weather station (XMR) rawinsonde data.

Through literature reviews and observational experience, Mr. Sardonia concluded that three primary factors are important in anvil formation:

- Average wind speed and direction in the anvil layer,
- Moisture content of the environment in which the anvil is forming, and
- Thunderstorm duration and intensity.

He first found some simple relationships between observed anvils and concurrent upper-air observations, and then used these findings in an effort to develop a method of forecasting anvils. The following sub-sections outline these steps. It is important to note that Mr. Sardonia's results are preliminary since they are based on a small data set and relate to attached anvils only.

3.1.1. Observational Relationships

Mr. Sardonia began an examination of GOES VIS data for thunderstorm and subsequent anvil formation. He then monitored the anvil growth through successive images until the anvil no longer increased in length. Using a utility in the Meteorological Interactive Data Display System (MIDDS), he determined the distance from the parent storm to the edge of the opaque part of the anvil (see Figure 3.1) and defined this length as the transport distance. Mr. Sardonia's determination of the edge of the opaque anvil was subjective and based on personal experience. He estimated a transport lifetime using the transport distance and the average wind speed in the 300 – 150 mb layer calculated from GOES sounder winds. At least three anvils of similar length and lifetime had to occur on the same day in order for the data from that day to be included in the data set.
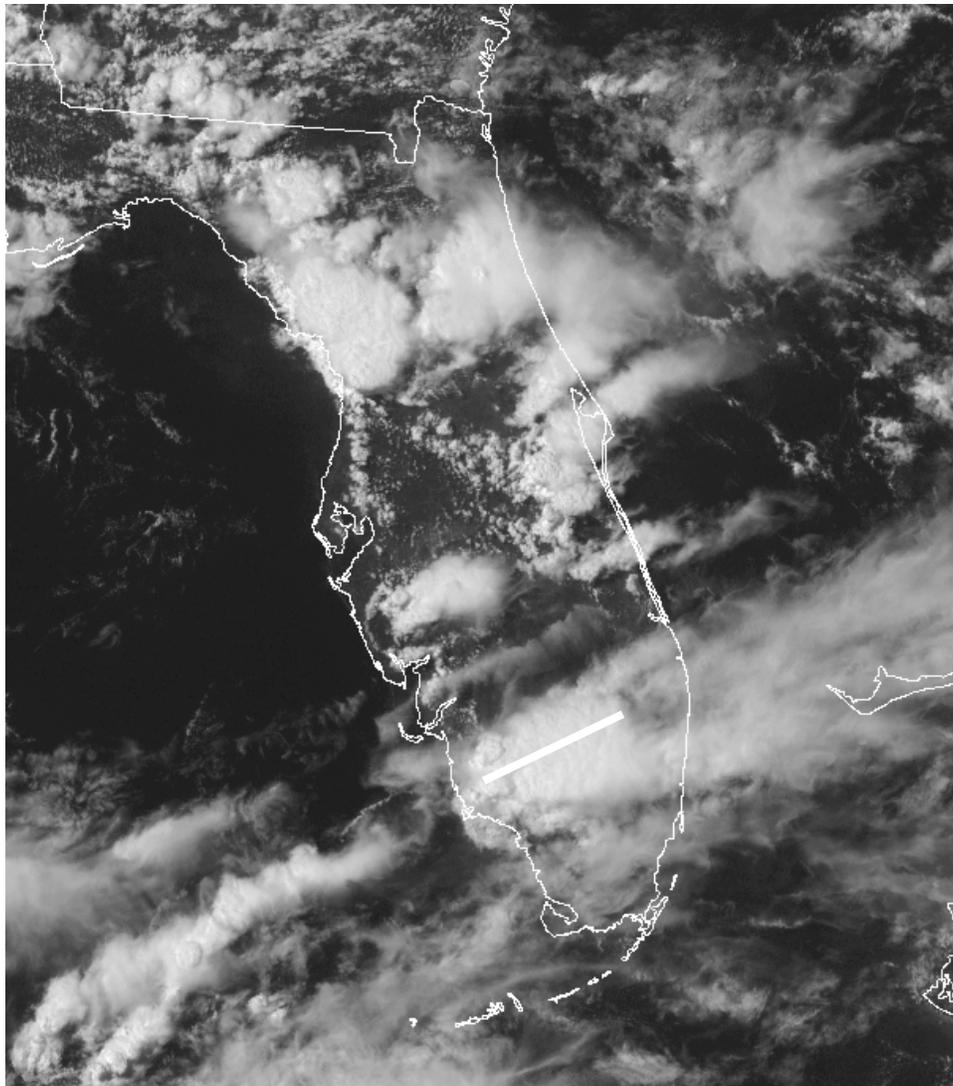
Figure 3.1.   VIS image from 12 June 1999 at 2000 UTC (1600 EDT). The line represents the transport distance of the anvil at its maximum length from the parent storm to the non-transparent edge.

Once an acceptable case-day was found, he collected and analyzed several data types that provided upper air information. GOES sounding data were used to determine correlations between the observations and anvil transport distance and lifetime derived from the VIS image. These data were found at the web site http://orbit-net.nesdis.noaa.gov/goes/soundings/html/sndbinary.html.   The GOES soundings are available every hour. These soundings are initialized with the temperature and dew point profiles from the Aviation (AVN) model then modified with data from the GOES sounder. The winds at each station for certain pressure levels are then calculated. Mr. Sardonia used the sounding from the location nearest to the parent storm and calculated the means for wind speed, wind direction, and dew point depression in the upper levels of the troposphere.

After a subjective analysis, he found that the mean values of wind speed, wind direction, and dew point depression (DD) in the 300 – 150 mb layer provided the best relationship to anvil length and lifetime. Figure 3.2 shows the relationship between anvil transport lifetime and the average DD in the 300 – 150 mb layer. Only a small number of cases were used (17), but there appears to be an inverse linear relationship between the values. The transport lifetime tends to be ≥ 2 hours when the DD is < 10° F and < 2 hours when the DD is > 10° F.

The black line on the graph in Figure 3.2 is the linear fit to the data. The equation of the line is of the form $y = mx+b$, where m is the slope of the line and b is the y-intercept. The coefficient of determination, R^2, is the fraction of the variance described by the linear regression. In simple linear regression, such as this case, the correlation coefficient is the square root of R^2.

The high value of R^2 in Figure 3.2 confirms the strong linear relationship between transport lifetime and DD in the 300 – 150 mb layer. The line, equation, and R^2 were calculated using the Trendline utility in Microsoft® Excel 2000. The equation and R^2 were calculated only to show the strength of the linear relationship and should not be used for anvil forecasting. The relationship and coefficient values are strictly preliminary.

Transport Lifetime vs. Average DD (300-150 mb)

$y = -5.5734x + 168.38$

$R^2 = 0.8114$
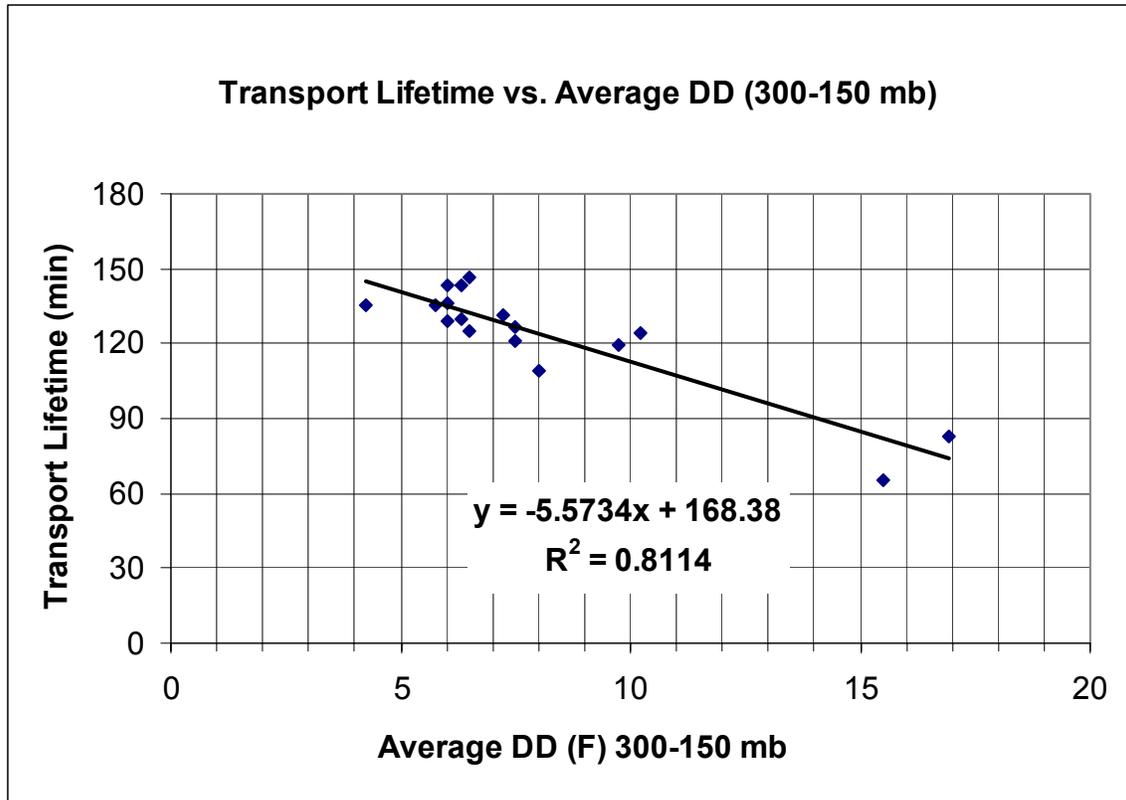
Figure 3.2.   Graph showing the inverse linear relationship between the transport lifetime and the average DD in the 300 – 150 mb layer. The blue diamonds represent the anvil cases. The equation of the line (y=mx+b) and the coefficient of determination (R^2) are also shown. The linear equation is preliminary and should not be used for anvil forecasting.

Figure 3.3 shows the relationship between anvil transport distance and the average wind speed in the 300 – 150 mb layer. The black line represents the linear fit to the data, and the equation of the line is shown. The high value of R^2 indicates a strong relationship between transport distance and wind speed. Mr. Sardonia also incorporated the data from the graph in Figure 3.2 to illustrate both relationships on one graph, and there appears to be a relationship between transport distance and DD as well. The blue lines mark the lifetime ranges in hours. Anvils (blue diamonds in the graph) that formed in an environment with a DD range of 10 – 20° F had lifetimes in the range of 1 – 2 hours, while those in the 5 – 10° F DD range had lifetimes in the range of 2 – 3 hours. Even though the data set is small, there is a strong indication that physically meaningful relationships exist between these observations.
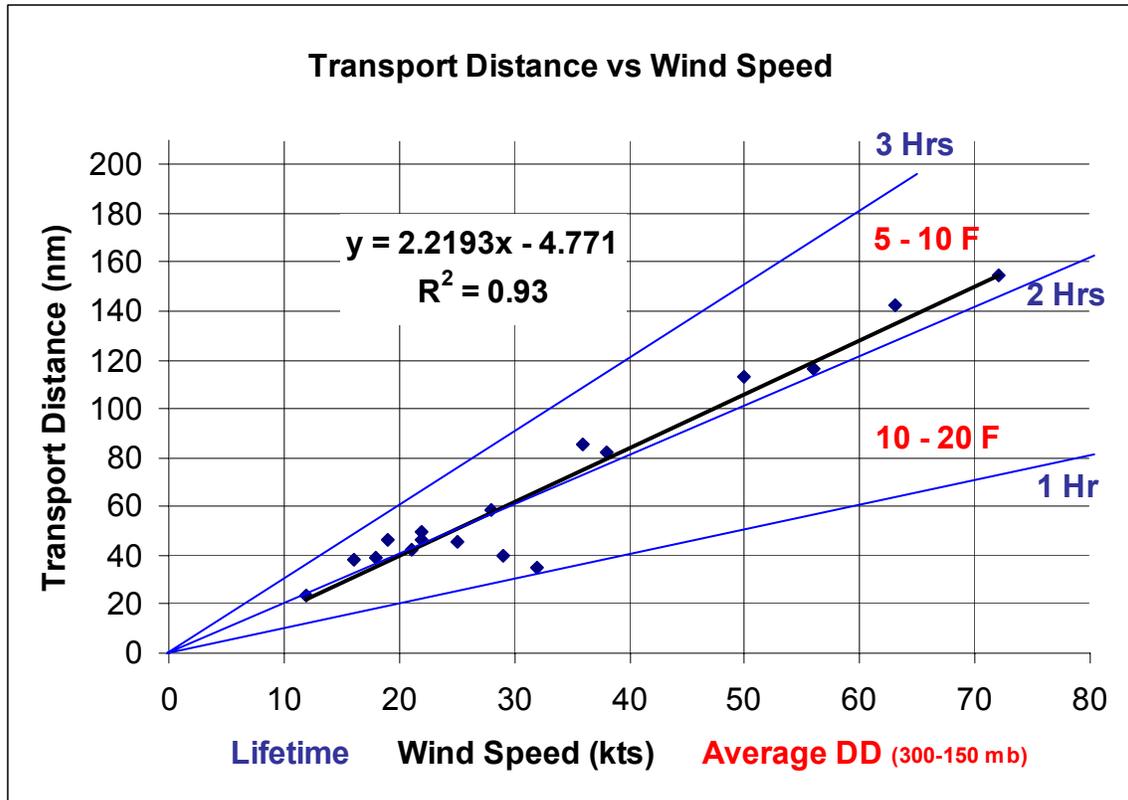
Figure 3.3.   Graph showing the relationship between the transport distance (anvil length) and the average wind speed in the 300 – 150 mb layer. The blue diamonds represent the anvil cases. The black line is the linear fit to the data points, the blue lines represent anvil lifetime, and temperatures represent DD ranges in the 300 – 150 mb layer. The equation of the line (y=mx+b) and the coefficient of determination (R^2) are also shown. The linear equation is preliminary and should not be used for anvil forecasting.

No relationships were found between average wind direction and either transport distance or lifetime, but it is important in determining the direction in which the anvil will develop.

3.1.2. Forecasting Relationships

Mr. Sardonia gathered the 1000 and 1500 UTC XMR rawinsonde and MRF, Eta, and RUC model forecast data in an effort to determine a method to forecast winds and moisture in the 300 – 150 mb layer at the time of anvil formation. He compared the rawinsonde and model forecast data to the GOES sounding observations. One test included averaging all the data types together and comparing them to the GOES sounding. Only eight case days were used in this test, but the values were very similar.

Figure 3.4 shows Mr. Sardonia's idea of how an anvil-forecasting graphic might look. The circle around the Cape represents any radius of interest. The box represents a corridor of concern. If thunderstorms develop anywhere within it, the Cape may be affected by anvils on that day. This box would be drawn based on wind speed/direction, moisture and thunderstorm intensity forecasts.
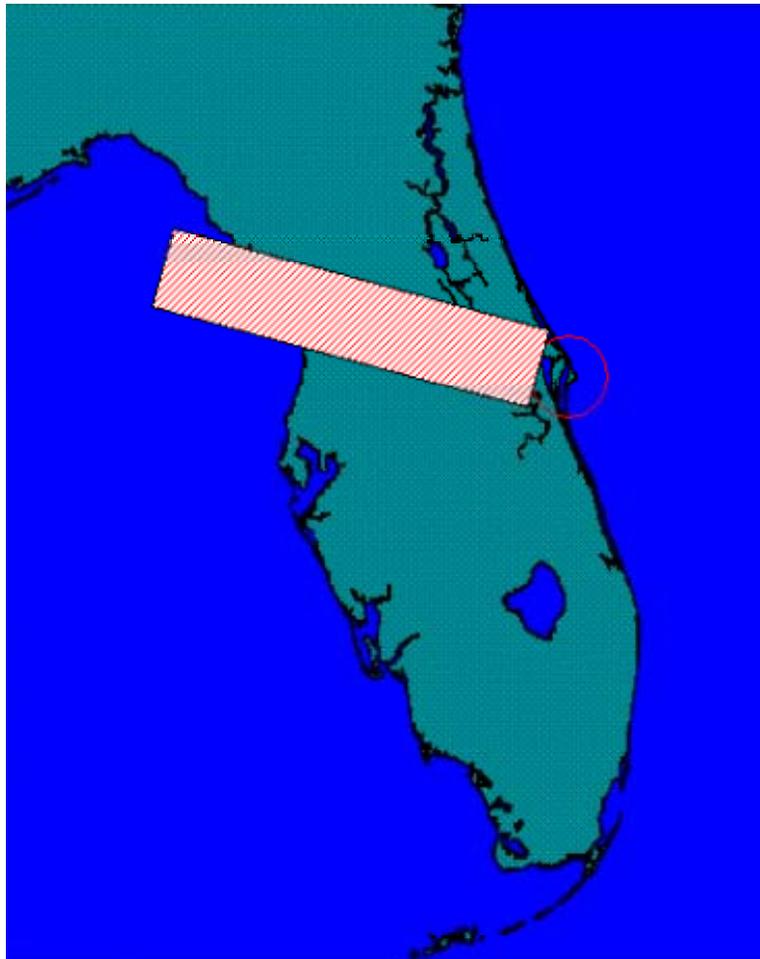
Figure 3.4.   Suggestion of how an anvil forecasting product might look. The circle around the Cape represents any radius of interest. The red and white striped box depicts a forecast area of concern. If thunderstorms form anywhere in that box, then anvils may affect the Cape.

3.1.3.   Thunderstorm Duration and Intensity

Sections 3.1.1 and 3.1.2 discuss observing and forecasting for the winds and moisture in the anvil layer, respectively. The third factor, thunderstorm duration and intensity, represents the most difficult aspects of convection to forecast and diagnose. The updraft strength and storm lifetime are both important in determining how many hydrometeors are being forced into the anvil and for how long. These, in turn, will likely have an effect on anvil length, lifetime, and opacity.

In the past, thunderstorms have continually formed over a small area in the Gulf of Mexico and the resulting anvils grew to lengths on the order of hundreds of kilometers. In one case, storms several hundred kilometers west of Tampa, FL produced an anvil that extended over KSC/CCAFS causing a launch to be scrubbed. Locations of such storms might be forecast by determining where upper-level divergence in the vicinity of a jet streak overlays an area of low-level convergence associated with a frontal boundary at the surface. A warm pool of water under that juncture could increase instability and add to the lifetime and intensity of the storms. Long anvils can also be produced by mesoscale convective systems (MCS). MCSs tend to form under high-pressure ridges at night and can last for hours, producing an anvil that could affect operations at KSC/CCAFS.

Short-lived intense storms can also produce long anvils. However, intensity is difficult to forecast and diagnose since the parameters important to intensity, such as updraft velocity and moisture content, are not directly measured. The LWOs made suggestions on how certain parameters and data types could be used to infer thunderstorm intensity. Model forecasts and observations of Convective Available Potential Energy, the Lifted Index, and the K-Index could be used before convection begins, and radar products could be used after the storms form.

3.2. Spaceflight Meteorology Group

The forecasters at SMG described three techniques they use to help forecast anvils: an anvil decision tree, an extrapolation/advection technique, and the use of operationally available data. They also had suggestions for how anvil-forecasting methods could be developed with a modeling study. All are described in the following subsections.

3.2.1.   Anvil Decision Tree

In an article for the 7th Conference on Aviation, Range, and Aerospace Meteorology (Garner et al. 1997), co-authors from SMG and the 45 WS described the issues and problems involved in forecasting detached anvils. They described using a detached anvil decision tree developed by the 45 WS to derive probabilities of detached anvil occurrence over and near Kennedy Space Center/Cape Canaveral Air Force Station (KSC/CCAFS). A simplified version of the decision tree from Garner et al. (1997) is shown in Figure 3.5. Forecasters must first determine if the probability of thunderstorm occurrence is greater than 0. If so, then the probability of detached opaque thunderstorm anvil (P(DOTA) – see Figure 3.5) is set equal to the probability of thunderstorm occurrence (P(TS)). The direction of flow aloft at anvil level is determined next. If storms are occurring or forecast to occur upstream of the area of interest, P(DOTA) is increased by 10%. If not, it remains equal to P(TS). Finally, forecasters might increase or decrease P(DOTA) based on the current meteorological conditions and personal forecasting experience.
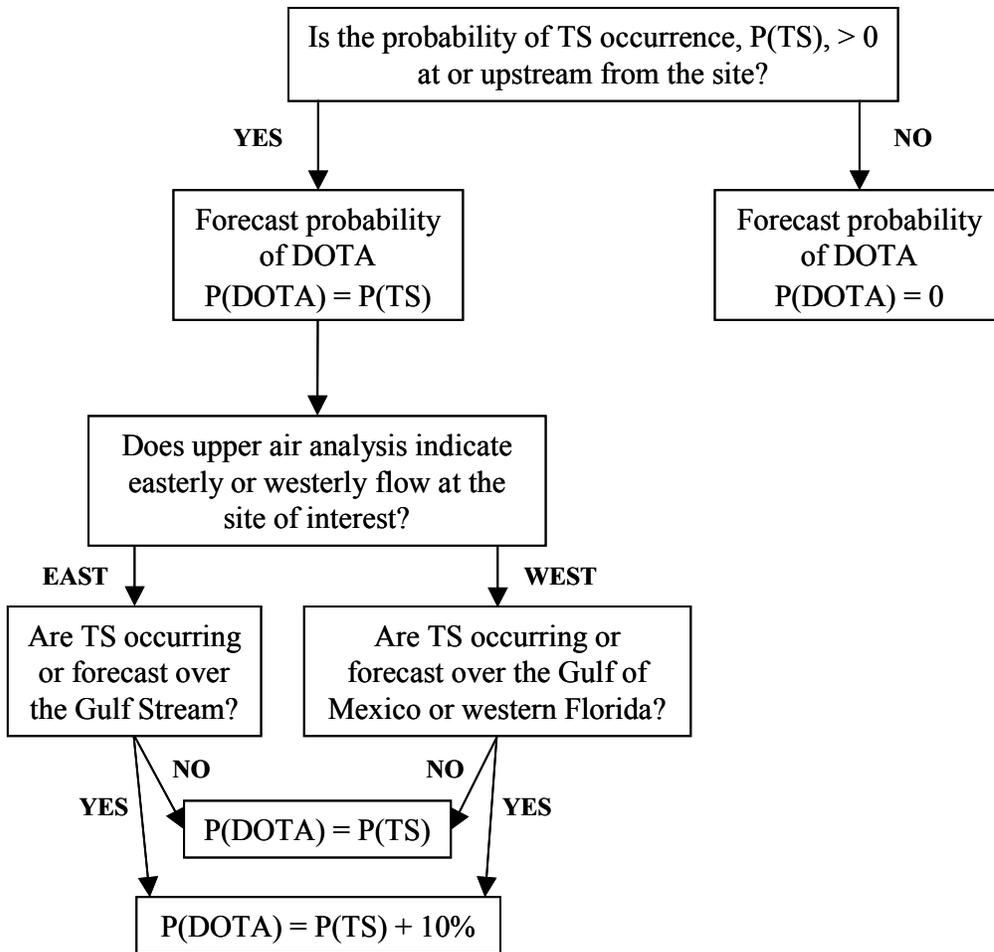
Figure 3.5.   Decision tree for forecasting detached thunderstorm anvils and other thunderstorm debris clouds at KSC. The acronyms are as follows: DOTA is Detached Opaque Thunderstorm Anvil, TS is thunderstorm, and P is probability.

The main strength of this technique is that it is quite simple to follow. However, the final probability is highly subjective since it will be ultimately based on forecaster experience and opinion.

3.2.2. Extrapolation / Advection

This technique requires an accurate analysis of the wind speed and direction in the upper-tropospheric layer that would contain the anvil cloud. Rawinsonde data from stations in Florida, data from the 50 MHz Doppler Radar Wind Profiler (DRWP), satellite-derived winds, gridded model output, and other data sources can be used for this analysis. Once the mean wind in the layer is determined, a circle with the Shuttle Landing Facility (SLF) or the launch pad of interest as the center may be drawn using the MIDDS applications DIST or CIRCLE. The radius of this circle should be the sum of two distances: 1) The distance defined by the FR or LCC, and 2) The distance over which an anvil would travel within the anvil age requirement, typically 3 hours. For example, if the mean wind is westerly at 50 kts, the radius from the SLF 3 hours prior to landing would be 170 nm ([3 hours × 50 nm/hour] + 20 nm). A wedge can be drawn in the upstream direction from the center to represent a region of interest based on the wind direction in the anvil layer. Figure 3.6 is a graphical example of this technique that can be overlaid onto satellite or radar imagery. Once anvils form, their motion may be determined by analyzing satellite or radar data animation loops, and the circle and wedge can be modified as the time of the operation approaches and to reflect any change in wind direction or speed aloft.
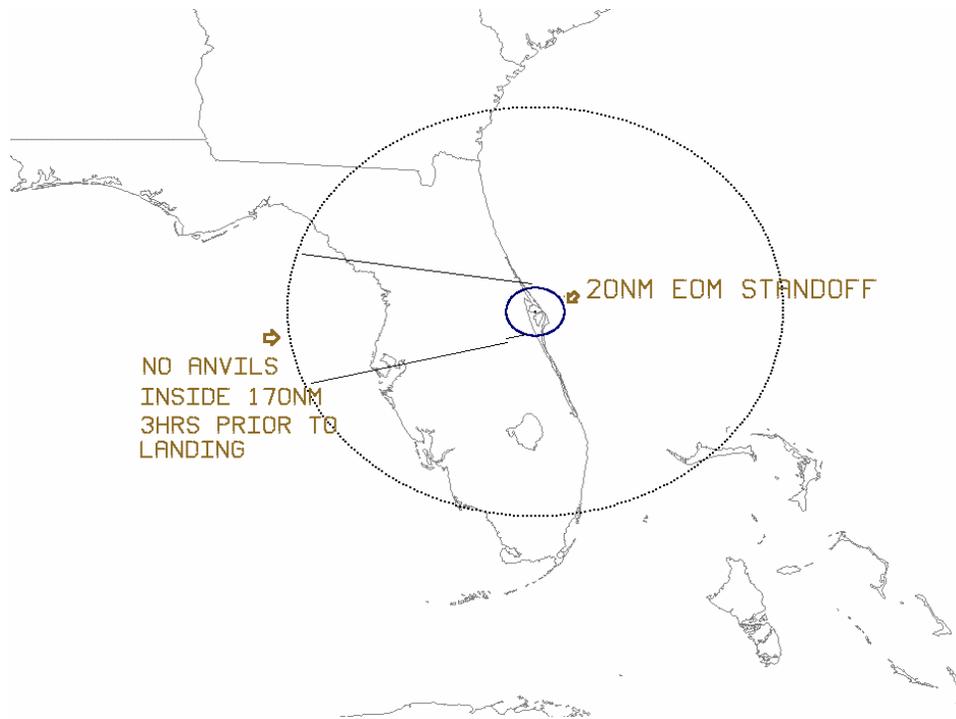
Figure 3.6.   The wedge extending west from KSC/CCAFS must remain anvil-free 3 hours prior to landing. It was drawn assuming westerly winds of 50 kts in the anvil cloud layer.

This method is relatively easy to implement and explain to users. However, the mean wind estimates must be accurate, particularly at very short ranges close to the time of the operation. Its main disadvantage is that it is a time extrapolation only. It accounts for anvil advection only, not anvil formation, diffusion, dissipation, time of detachment, opacity, etc. These anvil parameters must be subjectively determined by human observation.

3.2.3. Effective Tools and Products

Satellite imagery is used by SMG to monitor the initiation, growth, and decay of anvils. For this they use animations of infrared (IR) and visible imagery and GOES Channel 2 images as a tool for determining what clouds are composed of ice. Weather Surveillance Radar-1988 Doppler (WSR-88D) products and product animations are also useful for anvil analyses. High- to mid-elevation layer composite reflectivity data, high elevation angle base reflectivity images, vertical cross-sections of reflectivity, and composite reflectivity images are used for tracking anvils. Garner et al. (1997) states that the 10 dBZ contour marks the location of a non-transparent anvil edge. Subjective analyses at SMG since this article was written suggest that 5 dBZ may be a more appropriate definition.

SMG forecasters use Nested Grid Model (NGM), RUC, and Eta model output to help forecast whether anvils will affect KSC/CCAFS. Model forecasts of convective precipitation are used to approximate the location of initial thunderstorm development 6 hours or more before the launch or landing. Model profiles of temperature, dew point temperature, wind speed and direction at certain locations, and model time/height series of RH, cloud parameters, wind speed and direction, and temperature are used as tools for predicting winds and the thermodynamic environment of anvil layers. However, as thunderstorms form, some may become strong enough to modify the larger scale environment. Model data may be of less use in these cases.

3.2.4. Modeling Study

The forecasters at SMG recommended a modeling study to develop an anvil forecasting technique, using observations for model validation. A non-hydrostatic, high-resolution model that can explicitly simulate thunderstorm and anvil clouds is required.

One option is to use the Regional Atmospheric Modeling System (RAMS), currently running in real-time on the Eastern Range. This version of RAMS is configured with nested grids at 5-km and 1.25-km and full microphysics to forecast the behavior and interaction of cloud and precipitation particles. It would be possible to develop an anvil forecasting technique with the current version of RAMS by examining model output in real-time from both the 0000 and 1200 UTC forecast cycles over a period of several months. During the real-time data collection, the AMU would identify cases when RAMS predicts thunderstorm and anvil clouds and record forecast parameters relating to anvil formation, propagation, and decay such as upper-level wind speed/direction and RH, storm updraft strength, and cloud particle concentrations.

Another possibility is to simulate idealized cases using a model installed on an AMU workstation, such as RAMS or the Advanced Regional Prediction System (ARPS). Model input parameters could be controlled and changed for sensitivity studies to determine what meteorological parameters are important for anvil formation.

In any modeling study, it is important to verify the model forecasts with observations. The operational RAMS convection and anvil forecasts can be verified easily with VIS and IR satellite data, and the upper-level 5 dBZ contour in the WSR-88D data (see Section 3.2.3). Both the operational and idealized case study output can be verified with airborne field mill experiment data (summer 2000), should that experiment be successful in sampling anvils.

3.3. National Weather Service, Melbourne, Florida

Forecasters at NWS MLB are concerned with forecasting cirrus, of which thunderstorm anvils is a subset, as it relates to high temperature and cloud cover forecasts. If opaque cirrus clouds are present, the surface temperature and any future convective development will be affected. They use all available model forecasts of RH, wind speed and direction, and divergence in the 350 – 200 mb layer. They can expect to find cirrus where the upper-level divergence is strongest, such as in jet-streak regions. Through their experience, they have found that the models produce fairly accurate wind field forecasts but do not do as well when forecasting locations of maximum RH in the upper-tropospheric levels. Therefore, they advise that the upper-level wind fields (including divergence, vertical motion) may be much more useful than RH

when developing a cirrus and/or anvil forecasting technique using model output.

4. Summary, Conclusions, and Recommendations

This section assimilates the knowledge gained through the literature search and forecaster discussions. A brief summary of the report is given first followed by the statement of technical feasibility.

4.1. Report Summary

This report describes the steps taken to determine the technical feasibility of developing an anvil forecasting method or tool. The first step involved a literature search to find existing anvil forecasting techniques and information on anvil studies. Unfortunately, no existing forecasting techniques were found. The second step entailed gathering information from the forecasters themselves on their experience, current analysis/forecasting methods, and ideas for how an improved method could be developed. These discussions revealed an array of methods and ideas on how forecasting is currently done and how better techniques could be developed.

No anvil forecasting techniques were found in the literature. Articles were found that discussed anvil properties and can be separated into the two categories of observational and modeling studies. The observational studies measured several different aspects of anvils including heat/moisture budgets, ice water content, and electrification using both in situ and remote sensing instruments. One modeling study proposed the creation of a cirrus parameterization scheme and two modeling studies unsuccessfully modeled the microphysics and location of anvils. Most of the studies in both categories concluded that more studies of anvils must be done to understand their behavior. Also, all of the articles are dated from the 1980s onward. This may indicate a growing interest in thunderstorm anvils. If so, more articles about anvil parameters will be written and more information will be available to aid in developing a reliable anvil-forecasting tool.

The forecasters have ideas based on sound meteorological principles and a great deal of personal experience in forecasting and analyzing anvils. The observational technique proposed by Mr. Sardonia (Section 3.1.1), although still in the early development stage, shows promising linear relationships between the observed upper-level wind and RH fields and anvil length and lifetime, respectively. There are two options for conducting a modeling study as suggested by SMG (Section 3.2.4), both of which can take advantage of currently available local operational and experimental models. A modeling study may help determine what meteorological parameters are important for anvil formation. This would, in turn, benefit an observational study by defining what observed data are needed to develop an observations-based anvil-forecasting tool.

4.2. Technical Feasibility

Based on the information gathered in the discussions with the forecasters, the conclusion of this report is that it is technically feasible at this time to develop an anvil forecasting technique that will significantly contribute to the confidence in anvil forecasts.

4.3. Analysis of New Methods

Currently, the forecasters analyze in situ, remote sensing, and human observations and model output in various ways to help determine if non-transparent anvils will affect an operation. Although their techniques are used on a regular basis, none have been formally tested or verified to be accurate. The forecasters agree that an objective anvil forecasting method is needed. With that in mind, the forecasters had two basic suggestions for methods and their development. The first is an observations-based study and the second is a modeling study. The modeling study can further divided into two separate studies: 1) analyze output from the operational RAMS, and 2) conduct idealized case studies with a model installed on an AMU workstation. The following subsections describe the advantages, disadvantages, and likelihood of success of each of the three methods.

4.3.1. Observations-Based Study

Mr. Jim Sardonia of the 45 WS found some simple relationships between observed anvil length and lifetime and the average wind speed/direction and moisture content in the anvil layer. A complete description of this technique is given in Section 3.1.1 of this report.

Advantages

- A small data set has already been collected and the statistical relationships found from these data are very promising.

- Mr. Sardonia has already developed a simple, consistent method of selecting cases and useful data types.

Disadvantages

- More data is needed to develop operationally useful relationships. Data must be collected during a warm season in order to increase the sample size. If necessary, subsequent warm season data sets should be collected to have a sufficient number of cases from which reliable statistics can be calculated. The disadvantage is that time is needed to collect a sufficient data set, and it may require collection over more than one warm season.

- Development of the technique is still in the beginning stages and has so far only included the portion of the anvil that spreads downwind of the parent storm. Future work should consider that part of the anvil that spreads laterally and upwind.

- Determination of non-transparent/transparent anvil edge is subjective and not repeatable to an exact degree. A more objective method should be developed for this analysis, although it may be difficult if the non-transparent anvil edge determined by satellite data may not agree with the actual edge.

Likelihood of Success

The likelihood of success for the development of the product as proposed is high based on the promising linear relationships found with the current small data set. Once enough data are collected, more reliable relationships can be calculated and a simple product, similar to that in Figure 3.4, can be developed.

4.3.2. Operational RAMS Modeling Study

The first modeling study option is to use the operational RAMS. During the real-time data collection, the AMU would identify cases when RAMS predicts thunderstorm and anvil clouds and record forecast parameters relating to anvil formation, propagation, and decay such as upper-level wind speed/direction and RH, storm updraft strength, and cloud particle concentrations.

Advantages

- Variables that are not normally available from the observations, such as vertical velocity or cloud particle mixing ratios, can be examined from the model output.

- The operational RAMS convection and anvil forecasts can be verified easily with VIS and IR satellite data, the upper-level 5 dBZ contour in the WSR-88D data (see Section 3.2.3), and airborne field mill experiment data (summer 2000).

Disadvantages

- Models tend not to forecast the location and timing of convection very well. In order to forecast anvil occurrence, the model needs to be reasonably accurate at forecasting the parent storm. This may or may not be a problem with RAMS.

- RAMS currently uses a 4-grid configuration each with a different spatial resolution. An explicit microphysics scheme is used on all 4 grids, but a cumulus parameterization is used on the outer 3 grids only. As a thunderstorm forms and propagates it could move into grids with higher or lower resolutions and different physical parameterizations. It is unknown if this will have a negative effect on the simulation of convection and anvils.

- The results may be erroneous if RAMS does not have the correct physics to simulate some aspects of anvil formation, propagation, and decay.

Likelihood of Success

The likelihood of success of being able to use RAMS itself as an anvil forecasting tool is unknown. However, it may prove to be a useful tool in analyzing anvil behavior. In addition, there may be model forecast parameters, such as upper-level winds and RH, that will prove highly useful in developing an anvil-forecasting tool.

4.3.3. Idealized Cases Modeling Study

Another possibility is to simulate idealized cases using a model installed on an AMU workstation, such as RAMS or ARPS. Model input parameters could be controlled and changed for sensitivity studies to determine what meteorological parameters are important for anvil formation.

Advantages

- The ARPS model is already installed on an AMU workstation and can be configured for an idealized study.

- As with the operational RAMS study, variables that are not normally available through standard observations can be examined.

- An idealized study offers more control over the initial conditions. Several variables and ranges of variable values can be tested to determine which have the largest effect on anvil formation, growth, and decay.

- An idealized study in 2- or 3-dimensions could be executed more quickly than an operational modeling study since simulations can be done and analyzed without waiting for actual anvil cases to occur.

Disadvantages

- As with RAMS, the results may be erroneous if ARPS does not have the correct physics to simulate some aspects of anvil formation, propagation, and decay.

- There is less realism in idealized case studies, especially 2-dimensional simulations.

Likelihood of Success

The likelihood of success of being able to use ARPS itself as an anvil-forecasting tool is unknown. However, like RAMS it may prove to be a useful tool in analyzing anvil behavior, and compared to the operational RAMS study, it can be done more quickly.

4.4. Phase II Recommendation

Each of these studies can be done separately or in any combination. The AMU recommends that phase II of the task start with data collection for an observations-based study. The development of an observations-based technique has a high likelihood of success based on the promising relationships already found.

The likelihood of success for a modeling component of this task is not known. If the model does not have the appropriate physics to simulate anvils correctly it may not be as useful for identifying the parameters and the range of parameter values important for anvil formation, growth, and decay. Before collecting real-time RAMS forecast data for an entire warm season or running idealized cases, it is important to determine if the model can accurately simulate anvil life cycles based on conventional and/or special observations. This analysis will require comparison of specific forecast parameters such as wind, RH, and cloud properties with observational data for selected cases. If the results are favorable, then collection of real-time RAMS data and idealized modeling studies should be pursued.

If the AMU is tasked with a Phase II, the observational study may be conducted differently from that described in this report. It may employ different statistical models than linear regression depending on patterns found in the larger data set. The end product may also be different than that suggested in Figure 3.4. All testing and results in this procedure are highly preliminary and will likely change as more data are collected. During the work plan development and actual task work suggestions on how to best develop an anvil forecasting tool will be solicited from all forecasters for both the observational and modeling studies.

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APPENDIX A

LCC and FR Definitions

A.1. Anvil Launch Commit Criteria

Through the Lightning Advisory Panel (LAP), the 45 WS has developed a set of natural and triggered LCCs (Krider et al. 1999). The document describes separate LCCs for the two categories of attached and detached anvils. These criteria apply to non-transparent anvils only.

There are three criteria that must be considered for a non-transparent attached anvil. First, at no time is a vehicle launched if its flight path will carry it through the non-transparent part of the anvil. Second, if the flight path will be within 5 nautical miles (nm) of the non-transparent part of an attached anvil, 3 hours must have passed after the last lightning discharge from the anvil or parent storm. The third and final criterion states that if the flight path will be within 10 nm of the anvil, 30 minutes must have passed after the last lightning discharge in the parent cloud or anvil cloud before the vehicle can be launched.

Four criteria govern launches when detached anvils exist. The first two govern flight through a non-transparent detached anvil. First, 3 hours must have passed after the anvil detached from the parent cloud before a vehicle can fly through it. Second, 4 hours must have passed after the last lightning discharge in the detached anvil itself before the flight path carries the vehicle through the anvil. The third criteria states that if the flight path will be within 5 nm of the non-transparent part of a detached anvil, 3 hours must have passed after the last lightning discharge in the parent storm, the anvil before detachment, or the anvil after detachment. This third criterion can be waived if

- There is at least one working field mill within 5 nm of the detached anvil,
- The absolute values of all field mill measurements at the surface within 5 nm of the anvil and flight path have been less than 1000 Volts/meter for at least 15 minutes, and
- The maximum radar echo from any part of the detached anvil within 5 nm of the flight path has been less than 10 dBZ for at least 15 minutes.

The fourth and final criterion states that if the flight path is within 10 nm of the non-transparent part of a detached anvil, 30 minutes must have passed after the last lightning discharge in the parent storm, the anvil before detachment, or the anvil after detachment.

A.2. Anvil Flight Rules

The FRs pertaining to anvils are summarized in Table A.1. The information in this table was obtained from a similar table in the Space Shuttle Operational Flight Rules document. As with LCCs, these criteria are concerned with non-transparent anvils only. The distances given in the table depend on the time period in which the observations and forecasts are made, the location being considered, and whether the anvil is attached or detached.

There are three distinct time periods of interest during a Shuttle mission when FRs are evaluated. These time periods are represented across the top of Table A.1 and are known as pre-launch, pre-deorbit, and post-deorbit. The pre-launch period is self-explanatory. The FRs considered during this time ensure that weather conditions will be safe in case the Shuttle must make an emergency landing sometime between launch and entering orbit. The pre-deorbit period begins as the Shuttle enters orbit and ends at the deorbit burn. The final post-deorbit period extends from the deorbit burn to landing. If the weather along the flight path to the chosen runway configuration deteriorates below the FR thresholds in the post-deorbit period, the runway configuration will be re-designated to the configuration with the best weather.

When the decision is made to launch or to execute a deorbit burn, the anvil FRs should be observed "GO" at the time of the decision and shall be forecast "GO" at the prescribed landing time. An observation/forecast is considered "GO" if attached and detached non-transparent anvils are observed/forecast to remain a certain distance away from the runway and Shuttle flight path at the decision time/during landing. The descriptions of the exact locations of these areas are given in the left column of Table A.1. The first defines a radius around the center of the primary runway. The second defines a lateral distance from the portion of the shuttle approach path that begins at 30 nm from the center of the primary runway. The vertical distance is from the top of the anvil to the shuttle flight path.

Area of Concern	Pre-Launch (RTLS, TAL)		Pre-Deorbit Burn (EOM, Daily PLS) Pre-Launch (AOA)		Post-Deorbit Burn Runway Re-designation Criteria	
	ATTACHED ANVIL	DETACHED ANVIL	ATTACHED ANVIL	DETACHED ANVIL	ATTACHED ANVIL	DETACHED ANVIL
Radial distance from center of runway	> 20	> 15	> 30	> 20	> 15	> 15
Lateral distance from approach path (from center of runway to 30 nm)	> 10	> 5	> 20	> 10	> 5	> 5
Vertical distance from top of cloud	> 2	> 2	> 2	> 2	> 2	> 2

Table A.1. Flight Rules associated with non-transparent anvils. The criteria for a detached anvil assume that the anvil is less than 3 hours old. Distances are in nautical miles (nm).

RTLS   Return to Launch Site (post-launch, pre-TAL)
TAL   Trans-oceanic Abort Landing (post-RTLS, pre-orbit)
AOA   Abort Once Around (post-orbit, after 1 orbit)
PLS   Planned Landing Site (chosen daily from 3 US landing sites – based on weather)
EOM   End of Mission (normal end of mission)

APPENDIX B

Literature Search Summary

B.1. Observational Studies

The observational studies measured several different aspects of anvils to include heat and moisture budgets; ice water content, ice particle size distributions, and ice particle concentrations; and electrification. Satellite and radar remote sensing systems as well as *in situ* aircraft and rawinsonde observations were used to measure and analyze anvil parameters. Most of the studies discussed in the following subsections concluded that more studies of anvil parameters must be done to fully understand their behavior.

B.1.1. Heat and Moisture Budgets

Several studies used observations to address issues related to storm moisture and heat budgets. Johnson and Young (1983) used rawinsonde data to determine the apparent heat source and moisture sink for tropical anvils. The vertical heating and moistening distributions in anvils are different from those in cumulonimbus convection. Therefore, they ascertained that a proper partitioning of the total convective heating might be very important for improving the parameterization of convection in large-scale models. A relationship between anvil ice mass and radar reflectivity was developed in Heymsfield and Palmer (1986) using microphysical data from an instrumented aircraft and reflectivity data from a ground-based radar. They argued that the portion of ice mass transported into the anvil could be a significant fraction of the storm total water mass and that the development of an ice mass/reflectivity relationship would aid in future studies of storm water budgets. Heymsfield and Miller (1988) then used that relationship, along with rawinsonde observations and wind data from a ground-based Doppler radar, to examine the flow of ice into anvils of six thunderstorms.

Bosart and Nielsen (1993) studied data from an operational rawinsonde that happened to penetrate a thunderstorm anvil. They were able to present strong evidence of nearly undiluted ascent of sub-cloud air to a level above the tropopause. This addresses an important climate issue of the role of upper tropospheric/lower stratospheric water vapor in the atmosphere's heat and moisture budgets. Another important issue raised by Bosart and Nielsen is the National Weather Service (NWS) operational cutoff of moisture data at levels where the RH falls below 20% or when the temperature is less than -40°C. They contend that scientific interest in the global distribution of water vapor is growing and that data measured at higher levels should be transmitted as well. Because of this limitation they were unable to make any definitive statements about the transport of water vapor into the stratosphere.

B.1.2. Anvil Microphysical Properties

The effects of clouds on shortwave and longwave radiation are due to their microphysical properties. Because of their large spatial extent, thunderstorm anvils have a strong influence on the earth's radiation balance. This has led to several studies of parameters such as ice water content, particle size spectrum and distribution, and ice water path. Using aircraft data, Heymsfield (1986) examined particle growth processes in a severe thunderstorm anvil. This study found a direct relationship between anvil particle size and storm intensity. By using a one-dimensional microphysical model, Chen et al. (1997) simulated the detailed microphysics and compared the results to aircraft observations from three anvil cases. Out of the three simulations, only one corresponded fairly well with the observations. Pueschel et al. (1997) also used aircraft data to measure the amount of small ice crystals and haze particles in an anvil since, as they state, as much as 53% of the total visible extinction could be due to the very small particles in the anvil. In an interesting twist, Blyth et al. (1999) proposed a method to estimate the loading of ice crystals into thunderstorm anvils and other cloud properties using satellite measurements of lightning frequency. Their results were very preliminary and they stated that more data and analyses were needed to determine if such relationships could be developed.

B.1.3.   Anvil Electrification

Marshall et al. (1989) and Byrne et al. (1989) were the only articles found that discussed anvil electrification. They analyzed data collected from balloon-borne electric field sensors attached to standard rawinsondes. Both studies were done to obtain information on the magnitude of charge in anvils, the spatial (vertical and horizontal) and temporal variation of the charge, and to determine how the charge in the anvil develops. Prior to these studies, there were few direct observations of the charge structure in anvils. In one study of the air motions in anvils, the research aircraft encountered triggered lightning (Detwiler and Heymsfield 1987). The microphysical and other meteorological parameters were measured at the site of the strike, but the authors stressed in their final conclusion that other anvil studies should be done before any of their measurements are generalized to any class of anvils.

B.1.4.   Aviation Interest

Lawson et al. (1998) state that there have been at least ten incidents since 1990 where jet aircraft have unexpectedly lost thrust in one or more turbofan engines while flying in a thunderstorm anvil. The exact cause of this loss of thrust, commonly called engine rollback, is still not known. In this study, they analyzed output from flight data recorders when rollback occurred during flight through an anvil and compared it to meteorological data taken at the same time. The results suggest that these rollback incidents may be associated with engine ingestion of high concentrations of ice particles in the anvil.

B.2   Modeling Studies

One particular model, the High-Resolution Limited Area Model (HIRLAM), has been used in simulating cirrus clouds and anvils. Sigg (1995) used the model to try and determine the primary parameters and conditions that govern the formation of anvils. The study assumed that an anvil should be simulated by the model's stratiform parameterization scheme, that the temperature and relative humidity (RH) at the anvil level should be $\leq -20°C$ and $\geq 75\%$, respectively, and that the anvil area is as least as large as the parent cumulus cloud cover. When the simulations were compared to the observations, they found that the model under-produced anvils. They lowered the minimum RH threshold but found this did not eliminate the problem. They concluded that other conditions must be met for anvils to be simulated properly, but left the determination of those conditions to future studies.

Zurovac-Jevtić (1999) tested a cirrus parameterization scheme in HIRLAM in an effort to simulate high-level cirrus more correctly. It is widely acknowledged that large cirrus systems have a significant effect on the earth's radiation balance, but numerical models have known problems in simulating the upper-tropospheric moisture field. The developer states that the problems are caused by the poor or non-existent parameterization of cirrus. The introduction of a cirrus parameterization scheme may improve the forecasted upper-level moisture field. Although this scheme does not address the formation of anvil cirrus, an improvement in the upper-level moisture forecast would likely prove helpful in an anvil forecasting method.

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