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Panel on Meteorological Support for Space Operations
Board on Atmospheric Sciences and Climate
Commission on Physical Sciences, Mathematics, and Resources
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PANEL ON METEOROLOGICAL SUPPORT FOR SPACE OPERATIONS

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Preface

In response to a request from the National Aeronautics and Space Administration (NASA), the National Research Council (NRC) assembled a panel to review the meteorological support related to space operations at the Kennedy Space Center (KSC). A copy of the initial NASA request is included in Appendix A. Specifically, the panel was requested to review the requirements for meteorological information at KSC and to prepare recommendations for NASA regarding the feasibility, development, and implementation of a meteorological facility at KSC that would (1) improve the quality, utility, and reliability of meteorological information for planning and operations and (2) provide a facility at which atmospheric scientists may pursue short-term weather research to improve KSC operations.

In negotiations between NASA and the NRC, the scope of the task was broadened slightly. It was agreed that the panel would "review the state of scientific understanding of meteorological factors relevant to space operations at KSC, including existing observation and forecast systems and the utilization of meteorological information in decision making, identify potential improvements to the present system at KSC in terms of NASA requirements, and make specific recommendations for the development and implementation

of improved systems to address NASA's research and operational goals."*

This study is timely in that it follows the Space Shuttle *Challenger* explosion on January 28, 1986, and the lightning-related destruction of the Atlas-Centaur 67 rocket on March 26, 1987.

With recent advancements in ways to probe the atmosphere and the development of new avenues for processing, communicating, and interpreting meteorological information, much-improved meteorological support for space operations should be possible. This report reviews NASA's present program of meteorological support for space operations and offers suggestions for improvements.

The panel visited a number of sites during its study. In the period from August 31 to September 2, 1987, the panel visited the Kennedy Space Center; on October 30, interviews were conducted at NASA headquarters; and from December 1 to 3, 1987, the panel visited Johnson Space Center. Other meetings of the panel focused on the preparation of this report. A list of the persons who made presentations to the panel or were interviewed by the panel is included in Appendix B.

Although the study has been conducted for NASA, the panel has recognized that the report is likely to be read not only by NASA administrators and meteorological support personnel, but also by many other people with varying familiarity with the space program. Even among those working within the space program, there are varying degrees of familiarity with meteorological support operations. For this reason, the panel felt it would be useful to include a considerable amount of background information to provide an overview of the nature of meteorological support for space operations and the organizational environment in which it exists.

The Executive Summary reviews the principal conclusions and recommendations of the panel. Chapter 1 outlines the weather elements that are important for space operations and the manner in which they are critical. Chapter 2 contains an overview of the organizational structure of the weather support activities for the space program. Chapter 3 reviews the observational systems, and Chapter 4 suggests some possible technological upgrades for meteorological analysis and forecasting operations in support of space operations.

*From the proposal written in response to NASA's request for the NRC panel.

Chapter 5 outlines an organizational framework that the panel believes is needed to foster a vigorous and vital meteorological program in support of both manned and unmanned space flight.

I would like to thank the members of the panel for their conscientious attention to our deliberations. Each member attended all of the panel meetings and contributed significantly in the preparation of the text. I would like to acknowledge the role of Gregory S. Forbes, who assembled and reassembled the many drafts of the report. In addition, special thanks go to Karen Poniatowski and Arlene Peterson of the NASA Office of Space Flight for their assistance.

Charles L. Hosler, Chairman
Panel on Meteorological Support
for Space Operations

Contents

Executive Summary

Remote sensing and computer technologies have developed to the point where great new advances in real-time weather observing and forecasting are possible. An opportunity exists to make all phases of the manned and unmanned space programs more efficient, less threatened by delay, and free of weather-related hazards that could lead to damage or loss of spacecraft or even human lives. It is vital to make improvements within the meteorological support and launch decision infrastructure of NASA that may avert a repetition of tragedies such as the Atlas-Centaur 67 destruction on March 26, 1987, and the Space Shuttle *Challenger* explosion on January 28, 1986.

This report recommends mechanisms by which NASA can put into operation state-of-the-science meteorological technology and advanced weather forecasting techniques to enhance the efficiency, reliability, and safety of space operations. The spirit motivating these recommendations is the panel's belief that NASA should strive to exploit the benefits of the cutting edge of new meteorological technology, just as it exploits the potential of the numerous other technologies that support space flight. In striving to reach this goal, NASA can pave the way for many other applications of these advanced meteorological capabilities.

Since the inception of the shuttle program, the needs for meteorological support have become clearer and the quality of the meteorological support available has improved. However, it became obvious to all members of the panel early in this study that NASA has not had a coordinated meteorological support program. Owing to this lack of coordination, space program needs and meteorological expertise have not yet been adequately brought together.

The need for a coordinated and improved weather support program has already been expressed by others within NASA. In October 1986, the NASA Space Shuttle Weather Forecasting Advisory Panel (John Theon, chairman) issued its findings and recommendations to the NASA associate administrator for space flight. Their first and foremost recommendation was that "Shuttle weather services must be organized in such a way to bring them up to the very best state-of-the-science and technology and under an optimal management situation." Toward this end, they recommended that "NASA should establish a Weather Support Office at the top level of Shuttle operations to plan, organize, focus, and direct the activities related to Space Shuttle weather support." The Panel on Meteorological Support for Space Operations endorses this recommendation. (All recommendations from the Theon report are reproduced in Appendix C of this report.) In the report that follows, the panel amplifies some of these earlier findings and adds additional recommendations.

The task of reorganization will not be simple. Meteorological support for space operations is at present fragmented. The U.S. Air Force Air Weather Service provides observing and forecasting personnel at Kennedy Space Center (KSC), Vandenberg AFB, and Edwards AFB. NOAA provides support to Johnson Space Center (JSC). A private meteorological firm provides forecasting service for the Wallops Island, Virginia, Flight Facility. The Marshall Space Flight Center (MSFC) provides some technical guidance to both KSC and JSC, and other groups are also involved, including contractors. The various participants report to different organizations within NASA.

Following the Theon report and the formation of this panel, a Weather Support Office (WSO) was created within the Office of Space Flight (OSF), and on December 6, 1987, a director was appointed. To bring about substantial improvements in weather support, ***it is now imperative that NASA give clear and unambiguous authority to the WSO***, and grant it sufficient budget authority to

ensure an integrated and coordinated meteorological support program for all ground, launch, landing, and recovery activities. *Weather support for manned and unmanned space flight should be a single cohesive program coordinated through the Weather Support Office.*

This panel urges that all possible support be directed to this vital aspect of space operations. There are many good scientists and technicians involved in meteorological research and support activities within NASA, but they are not sufficiently focused on the operational problems of space flight. Each of NASA's research centers should be strongly encouraged to commit some of its resources in the effort to upgrade meteorological support for the space program.

Although Air Weather Service and National Weather Service forecasters have been supporting space operations with skill and dedication, the technology and techniques they have employed up to this time are not adequate to meet unique and stringent future requirements. Up to this point in the space program, launches have been relatively infrequent and delays have been accommodated. Thus it has, in principle, been possible to wait until ordinary meteorological observations have indicated an ideal launch window. However, there remains the concern that conventional techniques might fail to detect certain hazards. As launches are scheduled more frequently, delays will become less tolerable. There will be a need to identify a greater number of low-risk launch windows. This task requires improved observations and predictions of many special meteorological variables and phenomena of unique significance to space launches—e.g., triggered lightning, precipitation size and type, wind shear, and turbulence—with a degree of sensitivity, timeliness, and accuracy unique to the space program.

The panel offers the following recommendations so that as the space program moves into a revitalized era, space program personnel may use meteorological information with confidence during all phases of space operations. Recommendations are spelled out in greater detail in subsequent chapters, where expanded justification rationale is also given.

RECOMMENDATIONS

The panel identified five principal categories of deficiencies in the program of weather support for space operations:

1. Quantification of weather hazards.

2. Observing systems capable of detecting specific weather hazards.

3. Analysis and forecasting schemes for specific weather hazards.

4. Coordination of applications research and operational programs.

5. Organizational structure to promote continued improvement of weather support as needs change and capabilities improve.

A chapter in the report has been devoted to each of these principal deficiencies (although not exactly in the sequence presented here). The key recommendations addressing each of these problems are presented below. Additional observations and conclusions are highlighted within the chapters of the text.

> **Recommendation 1: With expectations of more frequent launches and an associated decrease in the margin of weather safety, it is imperative that NASA quantify more rigorously the relationships between magnitudes of weather variables and the hazards they pose to space vehicles. Flight rules and launch commit criteria should be based on these relationships.**

Many of the meteorological variables critically affecting space operations have not been adequately quantified to the point where weather support can be focused on specific threshold values. At the same time, Space Shuttle program managers have not defined precisely what weather information is needed. Thus the weather support system has not been able to concentrate sufficiently on the special problems of the Space Shuttle. Some critical parameters are currently not measured—such as drop sizes in clouds and rain, which are hazardous because of the possibility of protective tile damage—and there is no program to initiate these types of measurements. At the time when the Atlas-Centaur spacecraft was destroyed, NASA and the Air Weather Service were operating the largest network of electric field mills in the world, but measurements of electric fields had not yet been incorporated into the weather commit criteria as a guard against triggered lightning. Wind shear and turbulence criteria are also not quantitatively defined.

> **Recommendation 2: New and improved instrumentation must be used to detect weather conditions and phenomena that are hazardous to space operations.**

Many of the weather elements most critical to space operations are not being measured directly. Their existence is being inferred through relationships with other, directly observable, parameters. For example, lightning strikes in clouds, and the electric fields that provide a potential for triggered lightning in clouds, are inferred from surface-based electric field readings. Launch-time wind and wind shear hazards are estimated by using soundings prior to launch in conjunction with climatological statistics of expected short-term wind variance. These types of indirect hazard assessments are acceptable when no other options are available, but when more direct measurement systems are available they should be used.

Displays from additional existing lightning detection networks should be made available in the KSC weather forecast office, and a new system should be developed to detect in-cloud lightning. Instrumented aircraft should be used to measure electric fields aloft that could lead to triggered lightning and to measure the types and sizes of precipitation that could damage the Space Shuttle. Multiparameter radar and ground-based disdrometers should be used to examine the temporal and spatial variability of precipitation type and size. A network of wind profilers should be used to detect rapidly changing patterns of wind and wind shears or to ensure their nonexistence. Several Doppler radars should be deployed to detect probable areas of wind shear and turbulence and to identify low-level wind convergence zones in which thunderstorms are likely to form.

Alternative landing sites overseas have, until now, been equipped only with rudimentary instrumentation and have, in some cases, relied on local observers. These sites should be surveyed to ensure the availability of adequate weather observations for safe recovery.

Recommendation 3: A number of emerging techniques for weather analysis and forecasting and decision making must be actively pursued.

The introduction of new instrumentation should immediately improve detection capabilities, but it will not necessarily ensure improvements in weather forecasts. Present weather forecasting techniques have been developed for use with the types of data previously available and will need to be modified to incorporate new data bases. Improvements in knowledge of the quantitative relationships between weather elements and space flight risk will necessitate a fine-tuning of weather forecasts to accurately predict specific values of particular weather variables.

Techniques to be developed include a local weather analysis system, an interactive computer-aided decision-making system, and nested grid numerical weather prediction models.

> **Recommendation 4: To bring about substantial improvements in weather support, it is imperative that NASA give clear and unambiguous authority to the Weather Support Office and give it sufficient budgetary authority to ensure an integrated and coordinated meteorological support program for all phases of the manned and unmanned space programs.**

It has been made clear by the Theon report, and in all of the presentations heard by this panel, that the organizational structure of NASA has inhibited an integrated and coordinated weather support program that would focus NASA's considerable technological and human resources and expertise on NASA's operational space flight problems. The primary mission of the WSO should be to mobilize and coordinate as many of these resources as possible toward one objective: to develop and implement new technologies for observing, analyzing, and forecasting the weather elements most critical to the space program. In the context of this report, WSO should serve as the administrative office charged with ensuring the execution of the other recommendations.

> **Recommendation 5: An Applied Research and Forecasting Facility (ARFF) should be established at Kennedy Space Center to promote the development and application of new measurement technology and new weather analysis and forecasting techniques to improve weather support for space operations, to provide forecaster education and training, to coordinate field programs involving the meteorological community, and to conduct an active visiting scientist program.**

The paramount function of the Air Weather Service detachment at the Cape Canaveral Forecast Facility, which services KSC and the NOAA group at JSC, is to provide operational weather support on a daily basis for the many launches and ground activities in progress. Neither group has a mission to conduct research, and they are not adequately staffed to coordinate new programs to develop and install advanced instrumentation and new techniques for weather analysis and forecasting at KSC. However, the unique weather sensitivities of the space program dictate that new observing systems are required

in order to improve the quality of weather support. A great deal of effort is required to develop procedures for using these systems to improve operational weather analysis and forecasting and to train operational weather forecasters to use these procedures. Thus an ARFF is needed to help the WSO in the mission of developing new observing, analysis, and forecasting technologies. This assistance should include the special tasks of determining how best to use the technologies in the KSC environment and of transferring the technology to the operational forecast offices. These tasks should employ an experimental weather forecasting facility within ARFF where new techniques can be tested and operational forecasters can be stationed for training. An advisory committee should be formed to assess for WSO the ongoing efforts to improve weather support and to suggest additional or alternative approaches.

CONCLUDING REMARKS

The National Aeronautics and Space Administration has been poorly organized to provide weather support, and the result is a system that is less than state-of-the-science. Unless radical changes are made now in the way services and applied research are coordinated, weather will loom larger as a threat to a rejuvenated and accelerated space flight program. To make available greater numbers of safe launch and recovery windows and to provide a more complete recognition of hazards that are at present poorly observed and predicted, a larger, more comprehensive, and better integrated program will be required. This program will require rapid technology and technique development, testing, and transfer to operational status.

The panel believes that, in order to maximize the safety of launches of manned and unmanned vehicles and landings of the Space Shuttle, the space program most critically needs current weather information and forecasts valid for 2 hours or less. The quality of the latter very-short-term forecasts (or "nowcasts") is often, in reality, limited by the quality of the observations. Accordingly, the panel places the highest priorities on the improvement of existing observing systems and on the deployment of new measurement systems. Further, these actions can yield almost immediate improvements in weather support. Observations of lightning, electric fields aloft (in order to identify nonelectrified clouds that are safe to penetrate), and rapid wind variations are most urgently needed. The panel advocates

implementation of the following actions as rapidly as possible: instrumenting an aircraft to measure electric fields aloft, wind velocity, and turbulence along the launch/landing paths; installing a single wind profiler to detect sudden wind changes; and installing displays of additional lightning detection networks in the weather office to monitor thunderstorm systems approaching the KSC area. The development of forecasting techniques can follow, and benefit from, the new instrumentation.

Because of its high visibility, the space program is a critical focal point from which the public, the national and international scientific communities, and the nation's decision makers derive their perceptions of the scientific, engineering, and technological expertise in the United States. It is incumbent on all scientists and engineers to be sure that the best technology and expertise are utilized to ensure the success of the program.

1
Sensitivity of the Space Program to Weather Elements

On November 14, 1969, the Apollo 12 space vehicle was launched from complex 39A at the NASA Kennedy Space Center (KSC), Florida. At 36.5 seconds into the flight, and again at 52 seconds, major atmospheric electrical disturbances occurred that were subsequently attributed to vehicle-triggered lightning. Temporary disruptions of normal operations included the loss of attitude reference by the inertial platform in the spacecraft, illumination of many warning lights and alarms in the crew compartment, disconnection of the electronic circuitry to three fuel cells, loss of communication, and disturbances to the timing system, clocks, and other instrumentation. Nine nonessential instrument sensors with solid-state circuits were permanently damaged. It was most fortunate that the triggered lightning damage did not have disastrous consequences.

On March 26, 1987, an Atlas-Centaur unmanned vehicle was launched from pad 36B at Cape Canaveral Air Force Station. The weather conditions were similar to those present at the time of Apollo 12, and this time the outcome was calamitous. At 16:22:49 EST, about 48 seconds after liftoff, the vehicle initiated a four-stroke lightning flash to ground. This discharge caused a memory disruption in the vehicle guidance system that, in turn, initiated an unplanned yaw maneuver. The resulting exaggerated angle of attack produced stresses that caused the vehicle to break apart. About 70 seconds

after liftoff, the range safety officer ordered that the Atlas-Centaur be destroyed, in order to protect those below from large falling debris.

Both of these events illustrate that triggered lightning is currently one of the major forecasting problems at KSC. This threat may have already caused NASA managers to adopt an attitude of overconservatism to the extent that almost any cloud overhead may now merit the delay of a launch. Thus it is also important to know when clouds are benign and safe to fly through. There are also other weather phenomena (such as wind, wind shear, and precipitation) that may be hazards and that at present are not being observed or forecast adequately.

Space vehicle encounters with adverse weather conditions have been quite limited over the 30-year history of the space program, owing to a judicious selection of launch days, landing sites that usually favor benign weather environments, and the relatively short periods of time when the flight is in the weather-bearing layers of the atmosphere. The accumulated "exposure" time, amounting to a few minutes during each launch and up to an hour on manned reentry and landing, makes the total base of weather experience a few days at most. Until recent years, this limited weather experience had led to a belief that weather was of secondary importance in space operations. The panel hopes this perception no longer prevails.

Meteorologists realize that the space program has been relatively lucky with respect to weather hazards. Research in the last decade has revealed the occasional existence of various small-scale weather phenomena that could be dangerous to space flight, but often cannot be observed or forecast with existing operational instrumentation and techniques. The previous absence of encounters with these features over KSC has been partly a matter of chance. In view of recent temperature effects on O-rings and triggered lightning strikes, our run of good luck may have ended. Good luck need not be a requisite for acceptable space flight weather. It is the opinion of the panel that, with the introduction of new and upgraded observing, analysis, and forecasting tools, critical weather variables can be observed and launch conditions successfully predicted.

HISTORICAL PERSPECTIVE

If we reflect on the magnitude of the problem faced by the pioneers of space exploration and the history of the space program, it is

understandable that, when faced with the need to develop unprecedented mechanical, control, and communications systems, weather was not considered a high-priority problem. Prior to late 1987, no office was designated to coordinate weather-related operational needs, research, and related issues.

As entry into space has become more common, the character of the space program has changed in that the emphasis is turning to frequent launches, economical operations, reusable vehicles, and manned missions. These trends have increased the sensitivity of the space program to weather.

If the space program progresses into the 1990s as planned, two points are certain: (1) space flight will be more frequent, with delays and cancellations more intolerable and costly, and, as a result (2) encounters with potentially hazardous weather environments will be more frequent.

> **With more frequent launches and an expected decrease in the weather safety margin, it is imperative that NASA (1) more rigorously define the effects of weather on the space program and (2) take steps to upgrade its weather observing and forecasting program into a state-of-the-science system tuned to serve in this new era in space flight—a system that can confidently and reliably identify hazards as well as define launch windows with a high degree of weather safety.**

Historically, NASA has dealt with weather-related problems (1) by avoiding recognizable hazardous weather situations, (2) by reducing the sensitivity of the space vehicle systems to the weather ("system hardening"), and (3) by examining ways to change the weather. The panel certainly endorses further hardening of spacecraft systems. The Apollo 12 and Atlas-Centaur accidents have clearly demonstrated the vulnerability of spacecraft electronics to triggered lightning. A similar experience by NASA astronauts flying a NASA T-38A on February 24, 1987, in wintertime stratiform clouds near Los Alamitos Army Aviation Facility, California, shows that triggered lightning is pervasive.

Since the avoidance and hardening options have practical limits that fall short of ensuring total weather "immunity" and since modification of the weather does not appear to be practical at this time, the panel advocates improving weather observing and forecasting capabilities. Fortunately, bold initiatives are nothing extraordinary for the space program, and there is already evidence that NASA and

the cooperating agencies are taking steps to improve meteorological support.

In the remainder of this chapter the panel will lay the foundation for the future weather system by assessing the impact of numerous weather elements on various aspects of space operations. This will also provide the background for the subsequent chapters, which will map a strategy for implementing an effective, state-of-the-science weather observing and forecasting system.

WEATHER FACTORS IMPORTANT FOR SPACE OPERATIONS

Weather elements influence all phases of space operations, from mission planning through actual launch, booster rocket recovery (in the case of the Space Shuttle), and landing. Weather information is needed on time scales ranging from seasonal averages to seconds and spatial scales ranging from global size to meters. Each phase of the space program has weather sensitivities, some of which are described below.

Mission Planning

Years in advance of launch, space vehicles are designed and configured based upon climatological factors such as wind and temperature. Climatological wind profile statistics, which indicate the range of stresses that the vehicle is likely to encounter, are used in determining payload limits, flight trajectories, fuel requirements, and crew configuration. Other factors can influence the season or even the time of day scheduled for launch.

Ground Operations

Ground activities are sensitive to a number of weather phenomena. The temperature and wind profiles are critical factors in determining the hazards from fueling accidents because they determine the concentrations and trajectories of released gases. Activities involving toxic substances are curtailed when the resultant plume would threaten workers or a nearby population. Activities are also curtailed during the presence of nearby lightning or strong inversions (layers of air in which temperature increases with height) that could focus sound energy from explosions and cause window breakage.

Transport of equipment to and from the launch pads is curtailed during precipitation, lightning, strong winds, and blowing sand or dust. Fueling or detanking, as well as work on scaffolds, is halted by nearby lightning or winds exceeding 35 knots. Precautions must be taken for static electricity discharges during periods of low humidity.

Launch

Weather hazards encountered during launch can jeopardize the safety of the entire mission: launch pad, spacecraft, payload, and crew. Extended periods of low temperatures can inhibit the operation of some essential components. For example, temperatures on January 28, 1986, which were far colder than during any previous shuttle launch, have been determined to have contributed to the failure of the O-rings that led to the *Challenger* accident.* Stresses (wind loads) on structural members of the spacecraft that deviate significantly from those anticipated during planning stages (from climatological data) could cause the vehicle to deviate from course or break apart. Aerodynamic loads, from wind shears comparable to the largest previously encountered during launch and from vehicle response maneuvers, may have contributed to the final failure of the O-ring seals.** Precipitation drop impact during flight can damage heat-insulating tiles on the exterior of the Space Shuttle vehicle.

A direct lightning strike can damage the exterior of the space vehicle or the external tank of the shuttle. A nearby or direct strike can cause damage to the digitally controlled flight systems and other instrumentation, and even cause uncontrolled ignition of fuel. Both natural and triggered lightning are safety threats. Common cumulonimbus clouds and their anvils and deep nonconvective clouds can pose a threat of triggered lightning.

In order to avoid hazardous situations, weather is periodically reviewed during the countdown prior to launch. Weather conditions must meet stated criteria in order for the launch to proceed. If necessary, a launch can be delayed or postponed at any time until seconds before liftoff. The specific lists of weather launch criteria and flight rules have been under revision during the past several years,

**Report of the Presidential Commission on the Space Shuttle Challenger Accident*, June 6, 1986, pp. 70-72.

**Ibid.

with extra safety margins added to address the lightning threat and other hazards. The proposed launch commit criteria and flight rules are included as Appendix D.

Reentry and Landing

Landing operations include "normal" landings of the Space Shuttle involving reentry and end of mission (EOM), and "abnormal" landings, including missions aborted during ascent (return to launch site (RTLS)), trans-Atlantic landings (TAL), and abort once around (AOA) maneuvers. Unlike the ground and launch procedures, which can be delayed and resumed when conditions improve, the landing procedure, once begun, is irreversible. Thus the final weather decision and site selection must be made at least 90 minutes before the vehicle is due to land. Complicating the situation is that landing is the most sensitive phase of the space flight mission.

In the landing phase, all of the weather factors discussed with respect to launches are again important. In addition, many previously unimportant weather conditions become critical because the spacecraft may be piloted visually below 8000 feet. Low clouds and fog, haze or other sources of low visibility directly affect the suitability of sites for landing. These constraints present a significant susceptibility to even weak weather systems. Because the spacecraft has limited control capability during this stage, clear-air turbulence, or strong headwinds or crosswinds, can present difficulties. More obvious weather threats such as thunderstorm-related wind shears and lightning present an even greater risk to the spacecraft during the landing phase.

Rescue and Recovery at Sea

Booster rockets from the Space Shuttle normally fall into the sea and are recovered by ship. Observations or forecasts of adverse weather in the recovery region, such as high winds, low visibility, thunderstorms, or high sea conditions, would affect the launch decisions.

Postlanding Procedures

The landing does not end the weather threat to the spacecraft or space program personnel. In loading the orbiter onto the Shuttle Carrier Aircraft (SCA) and readying the SCA for transport, the

orbiter may be exposed to weather elements for a number of days. High winds, sandstorms, lightning, and precipitation can produce damage. Wind sensitivity is maximized while the orbiter is installed piggyback onto the SCA.

The SCA flight itself can be dangerous. Flights are limited to daylight hours at low altitudes, maximizing potential interaction with thunderstorms and turbulence.

Quantified Hazards from Weather Elements

As discussed previously, there are launch criteria and flight rules for a number of weather variables. It was very difficult, and perhaps beyond the scope of this panel's task, to determine how much data had been collected on the response of the shuttle (or other) vehicle in a range of possible values of some of these parameters (e.g., precipitation types and sizes). Many of the weather elements are potentially disastrous to space flight, and the extent of the danger should be quantified as exactly as possible.

Unfortunately, it appeared to the panel that there is only crude quantitative data regarding the risk posed by some weather hazards, such as the values of cloud electric fields that are capable of producing spacecraft-triggered lightning. One dangerous byproduct of inadequate information on weather element-risk relationships may be a tendency for the launch director to issue waivers of launch criteria when conditions seem to be marginal; on average, two waivers have been issued for each shuttle launch to date. It would be far better to base decisions on the analysis of a complete data base.

New launch and landing weather flight rules have been developed that effectively prevent launch or landing if there is any thunderstorm-produced cloud nearby. The panel is concerned that the implementation of overcautious flight rules will so constrain the opportunities for launch that the launch director will ultimately have no choice except to issue waivers. The development of quantified weather element-risk relationships advocated above would provide the best basis from which to define launch criteria and flight rules. Only through use of these relationships can optimum flight rules be attained, balancing the need to launch (i.e., the acceptable risk), the need for safety, and the extent of risk posed by a given weather situation.

A review should be conducted to determine whether or not the detailed responses of the Space Shuttle and other space

vehicles to expected ranges of meteorological parameters are known and are accurate. The results of well-posed studies should be quantified and published and used as the basis for launch commit criteria.

If the review shows that previous studies of weather hazards have been inadequate, then new data should be collected to quantify the chances of vehicle damage and/or a catastrophe as a function of the observed values of various meteorological parameters and their time-space distributions.

In some cases existing data bases are not adequate to establish appropriate flight rules. An example of a phenomenon where additional data are needed is lightning triggered within and near the clouds produced by distant thunderstorms. In order to make real-time launch decisions, data are needed to show the probability of triggered lightning as a function of distance to the parent thunderstorm, in combination with surface and airborne electric field measurements and other parameters that can be observed.

CLIMATOLOGY OF CRITICAL WEATHER ELEMENTS

Climatological data can provide important guidance in scheduling activities to minimize weather hazards. For example, Figure 1, a graph of the number of lightning strokes as a function of time of day, reveals that threats from natural lightning could be minimized by scheduling launches only between 0300 and 1500 UT (10:00 p.m. and 10:00 a.m. EST).

New climatological data bases are needed for weather elements used in the newly revised flight rules and launch criteria. Most of the data needed for an effective climatology of this type do not yet exist and require obtaining data sets from new sensors. Among the data needed are the types and sizes of precipitation elements in various kinds of clouds, the electrical fields within and near detached anvils and a variety of other cloud types, the electric fields that are required to produce triggered lightning, and the magnitude of wind variations on a variety of time scales. The sensors that may be used to collect these data bases are discussed in Chapter 3.

As the extent of new weather hazards is quantified, and as new launch criteria and flight rules are established, climatological data bases should be generated that show their seasonal and diurnal frequencies. It is clear that data bases

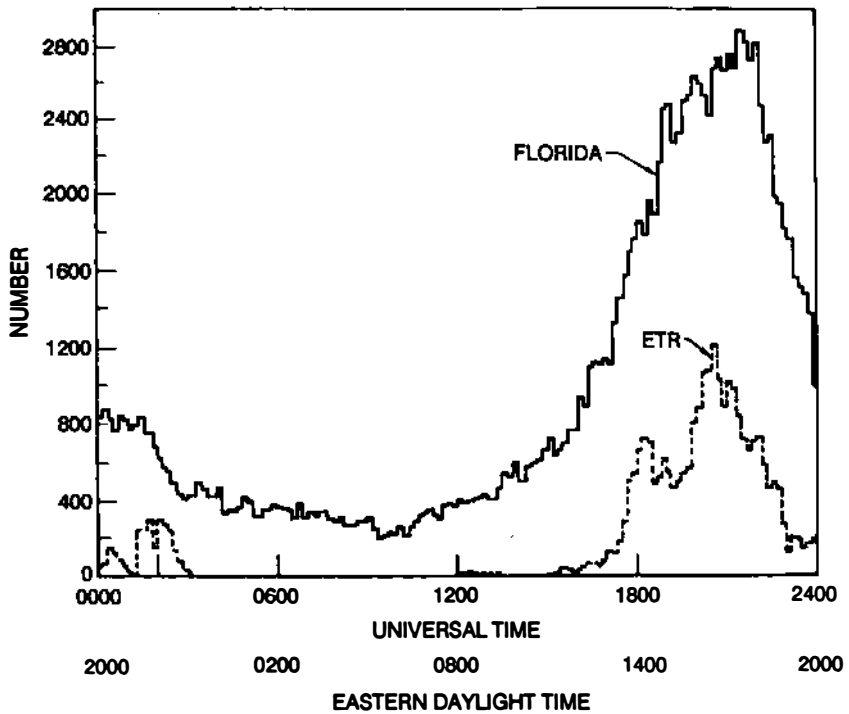

FIGURE 1 Variations in the number of summer lightning discharges as a function of time of day. The dashed plot represents the cumulative number of lightning flashes detected over the Eastern Test Range (ETR) using the field mill network (Launch Pad Lightning Warning System (LPLWS)) during the summers of 1976 to 1980. The solid plot represents the cumulative number of lightning flashes detected over southern Florida using the Lightning Location and Protection System (LLP) from June 15 to August 31, 1978. Data were tabulated in 10-minute intervals. (From Maier, L.M., E.P. Krider, and M.W. Maier. 1984. Average diurnal variation of summer lightning over the Florida Peninsula. *Mon. Weather Rev. 112*:1134-1140.)

are needed that characterize the triggered lightning hazard, electric fields within and near a variety of cloud types, precipitation types and sizes, and short-term wind variability.

One existing climatological data base may need expansion. The present use of winds in the loads program has some inherent limitations. Wind variability statistics invoked in determining the likelihood of hazardous loads on the spacecraft ("knockdown loads") are based upon pairs of jimsphere wind profiles obtained about 3.5 hours and 1.7 hours apart. (The jimsphere is a roughened balloon designed

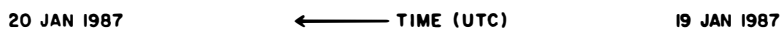

FIGURE 2 Time-height section of wind speeds (knots) obtained from hourly wind profiler data at Pennsylvania State University on January 19-20, 1987. The stippling indicates a 100-knot change of wind speed in 2 hours. For comparison, also indicated are the times of twice-daily National Weather Service rawinsonde launches at sites across the United States. The latter observations, taken about 400 km and 12 hours apart, can easily miss siguificant atmospheric features. (Courtesy of G. Forbes, Pennsylvania State University.)

to respond rapidly to wind changes.) Pairs are pooled by season, and sample sizes range from 37 to 65.

The panel is concerned that the jimsphere-pair sample is biased toward fair weather days in general, and to warm days during the winter season, the types of days most typically used for launches in the past. Sharp, dangerous jet streaks, relatively small (500 to 1000 km) wedges of high wind speeds with strong vertical shears, such as illustrated in Figure 2, are typically associated with disturbed weather and may not have been adequately represented in a sample biased toward warm, fair weather occasions.

An accelerated launch schedule will tend to require launches on some less-than-perfect occasions, and the present jimsphere pairs underestimate the wind shear hazard on those types of days. The

winter season is likely to bear the brunt of the heightened schedule, as thunderstorms, their rapidly changing weather, and the associated forecasting difficulties make it difficult to increase the pace during the warm season. The jimsphere pair data base should be expanded during the winter season to include all types of days that meet the other weather criteria for launch. It is especially critical that the data base include cases of clear skies immediately following cold front passage, where strong turbulent jet streaks are often found.

The jimsphere-pair data base should be expanded, especially during the winter season, and should be supplemented by wind profiler data.

2
Organization of Weather Support Services

Weather-related activities in support of space operations are conducted within a complex web of agency infrastructure. Several government agencies have responsibilities for operational weather observing and forecasting, among them the United States Air Force Air Weather Service (USAF/AWS), the National Weather Service/ National Oceanic and Atmospheric Administration (NWS/NOAA), and the United States Army Atmospheric Sciences Laboratory (White Sands, New Mexico). Private contractors are also used to take observations at Kennedy Space Center (KSC), and NASA personnel at KSC provide support services. The U.S. Naval Oceanography Command has responsibility for operational forecasts of sea conditions for recovery and rescue operations. Meteorological research is done in a number of laboratories within the Air Force, NOAA, and NASA, and by university and private contractors.

The functional and fiscal hierarchies of meteorological support within these agencies are complex. Even though all of the agencies are funded by the same federal government and are working toward a common goal of excellence in providing weather services in support of space flight, in practice this does not ensure a well-coordinated effort. Many activities have evolved within individual subprograms of the organizational web, but, in the absence of an overall plan, serious gaps remain. The most fundamental conclusion of this report is that

meteorological research and operational support activities within the U.S. space program are not well coordinated.

The panel is not alone in reaching this conclusion, as this view was expressed to us at the operational level within each of the weather support agencies. These people know what needs to be done, but lack the line responsibility or financial or manpower resources to do it. There must be significantly better overall organization of the various weather-related activities in support of space flight.

NASA's Office of Space Flight (OSF) bears the responsibility for the construction, launch, control, and recovery of NASA's space vehicles. Within OSF there are separate programs for manned (National Space Transportation System, NSTS) and unmanned (ULV; or expendable, ELV) space flight, having common as well as unique weather sensitivities. In order to coordinate the weather-related activities for both manned and unmanned space vehicles, strong organizational control must come from an office that has responsibility for both manned and unmanned space flight. An advisory committee described in Chapter 5 may facilitate the intragency coordination.

The Weather Support Office (WSO) was created within the Office of Space Flight late in 1987 and has the responsibility for creating a more organized program of meteorological support. Although the WSO is shown within the manned space flight chain of command in Figure 3, it is important that all other segments of the Office of Space Flight coordinate their requirements for meteorological support through the WSO.

To facilitate the organizational procedure, everyone involved in meteorological support for space flight must recognize that the Weather Support Office has responsibility for directing, coordinating, and supervising the operational and applied research activities in support of both manned and unmanned space flight.

The director of WSO should seek to mobilize the wealth of talent and facilities within NASA, USAF/AWS, NOAA/NWS, and other government agencies and universities to address weather support problems.

The Weather Support Office must obtain a budget and exercise line-item authority to support and direct applied research efforts needed to solve operational weather problems.

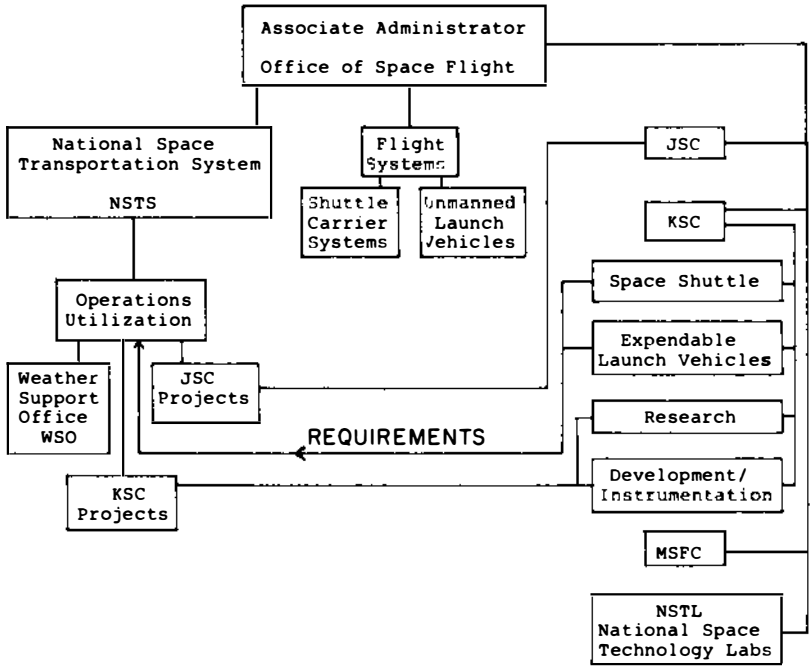

FIGURE 3 Schematic diagram depicting the portion of the NASA OSF organizational hierarchy that is most concerned with weather support activities. Many additional offices exist at each level of the hierarchy, and at additional levels, which have not been shown.

WEATHER OBSERVATIONS

The space vehicle launch and landing sites within the United States are shown in Table 1. There are numerous additional landing sites overseas for manned vehicles. Manned (Space Shuttle) and unmanned vehicles are launched into near-equatorial orbits from KSC. Unmanned vehicles are launched into polar orbits from Vandenberg AFB. Smaller unmanned rockets are also released from Wallops Island, Virginia, but the panel did not examine this program's weather support, which is provided by a private contractor.

Launches may not proceed without acceptable conditions at the launch site, at the scheduled landing site, and at other locations that would serve as landing sites in the event of abort once around (AOA), trans-Atlantic abort landings (TAL), or end of mission (EOM) decisions.

TABLE 1 Launch and Landing Sites Within the United States

	Launch	Landing
Kennedy Space Center, Florida (KSC)	X	X
Vandenberg AFB, California	X	
Edwards AFB, California		X
White Sands Space Harbor, New Mexico		X
Wallops Island, Virginia	X	

Detachments of the USAF/AWS are responsible for meteorological observations at the launch and landing sites, except for White Sands, which is the responsibility of the U.S. Army Atmospheric Sciences Laboratory. AWS also has the responsibility for weather observations at most of the other worldwide landing sites for manned vehicles. At KSC, the AWS uses a contractor, Pan American, to take surface and upper-air weather observations and service the field mill network and a number of other weather sensors deployed around KSC. These are described in Chapter 3.

The weather observations required for the space program are not routine. Many of the measurement systems are at the forefront of atmospheric science today. Thus the observers and maintenance personnel must be specifically qualified.

The total NASA observation and instrumentation program is not as well organized and supervised as it should be. For example, there is a lack of quality control: the one electric field mill site the panel was shown at KSC could not work properly because the sensor was mounted improperly and was too close to an electrical outlet and a rope fence. For another example, an aircraft is flown prior to each shuttle launch with minimal instrumentation; yet this same aircraft could be instrumented to make measurements of the electric fields in various types of clouds. The second example also illustrates a more widespread problem: although there is a wealth of talent and facilities within the agencies involved with the space program, the resources have not been adequately mobilized toward addressing operational weather problems at KSC.

The Weather Support Office should periodically (1) assess whether or not weather observations and observers meet the

needs of the space program, (2) conduct thorough inspections to determine if observing systems are properly configured, calibrated, and maintained, (3) ascertain whether or not available resources are being fully used to support space flight, and (4) take actions to correct any problems identified.

WEATHER ANALYSIS AND FORECASTING

At KSC, weather analysis and forecasting for daily ground operations, launches, and air-sea rescue efforts are the responsibilities of the Air Weather Service, 4th Weather Wing, 2nd Weather Squadron, Detachment 11, Patrick Air Force Base, and Cape Canaveral Forecast Facility. An exception is that Marshall Space Flight Center (MSFC) analyzes the prelaunch sounding data and furnishes them to JSC for use in the computer programs that calculate loads (stress/torque) on the launch vehicle.

Because of the large number of daily weather-sensitive activities and because both civilian (20 percent) and military (80 percent) vehicles are launched from KSC, the amount of work required is considerable. AWS officers and enlisted personnel, most reassigned at 2- to 3-year intervals, and two "permanent" civilians make up the weather forecasting staff at the Cape Canaveral Forecast Facility, which services KSC. Forecasts for unmanned launches are the responsibility of the AWS detachments at the launch site, either Cape Canaveral Forecast Facility or Vandenberg Environmental Support Center. Forecasts for occasions when the Space Shuttle is ferried from its landing site back to KSC are also the responsibility of AWS.

Once a Space Shuttle is launched, control of the mission transfers from KSC to JSC. Weather forecasting responsibility, even in the event of RTLS (Return to Launch Site, or "mission abort") or over-water ditching, rests with the NWS/NOAA Spaceflight Meteorology Group at JSC, although they coordinate and collaborate with their AWS counterparts at KSC. The NWS/NOAA team also has forecasting responsibility for all worldwide landing sites.

A team of nine meteorologists makes up the staff of the weather office of the Spaceflight Meteorology Group at JSC, of which three are primarily responsible for managing the Meteorological Interactive Data Display System (MIDDS), applications programming, and technology transfer. These three meteorologists constitute the Technique Development Unit at JSC, but when the panel visited JSC only one had been hired. When the Space Shuttle program resumes more

frequent launches, and in order to effectively use new techniques and technology proposed later in this report, the size of the staff will need to be increased.

The director of WSO should (1) ensure that forecast office staffing at all sites is adequate for the assigned tasks, especially as launch frequency is increased, and (2) conduct intraagency and interagency briefings to ensure that the various agencies with weather forecast and support responsibilities are properly coordinating with each other during manned and unmanned space operations.

APPLIED RESEARCH

The AWS and NWS forecast offices at KSC and JSC are operational units, not charged with research missions. Present staffing does not allow them to undertake applied research programs, aside from limited forecast studies and software development. Within AWS the latter activities are done by forecasters during slack operational periods. Within NWS, several staff members are dedicated to a Techniques Development Unit that performs these types of activities. Though the forecast offices cannot perform the needed applied research, the AWS and NWS forecasters should play a strong role in identifying problems and requirements for applied research and technique development directed toward carrying out their mission.

Larger applied research tasks are performed by other (nonforecaster) agency personnel or are contracted to universities or private agencies. Within NASA these efforts are funded by the Office of Space Flight at NASA headquarters, by the director of KSC or JSC or by project leaders at these centers, or by one of the other NASA centers (such as MSFC). In the past, MSFC has been responsible for weather technology transfer and technology utilization programs for NASA space flight. There are other major meteorological research programs within NASA that are outside the jurisdiction of the OSF, such as Goddard Space Flight Center, Langley Research Center, Ames Research Center, Lewis Research Center, and the Jet Propulsion Laboratory.

Within the Air Force, research is conducted and contracted by the Air Force Geophysics Laboratory (AFGL) or the Air Force Office of Scientific Research (AFOSR). A number of NOAA laboratories and cooperative institutes perform research on instrumentation systems and on diagnostic and prognostic techniques, some of which deal

specifically with KSC under contract, and others of which could be of use in a system tailored toward solving KSC's problems. Most of this research is generated within the individual unit and is not centrally directed.

On several occasions the panel encountered different views regarding the perceived versus actual roles of research agencies. Strong central coordination is required to ensure that applied research efforts are complementary rather than redundant, are directed toward solving operational needs, and are pursued to the stage where the results can be effectively applied toward solving operational problems.

The Weather Support Office should be staffed with atmospheric scientists who are capable of evaluating applied research activities, stimulating new applied research efforts needed to meet unaddressed needs of the space program, and coordinating these efforts.

3
Observing Systems

The weather sensitivities of the space program demand measurements of parameters quite different from those made for use in providing the public with weather forecasts. The types and sizes of precipitation particles in clouds and the potential for triggered lightning are just two examples. Because of the special requirements of the space program, certain deficiencies exist in the observational program at KSC and other sites that can be remedied by a combination of upgrading existing systems, acquiring and deploying new equipment now available, and conducting applied research to develop needed equipment not yet available anywhere in the world. These activities range from adding displays and calibrating instruments, which could be accomplished in a few days, to applied research that could take a few years. Improvements should be planned and coordinated by the Weather Support Office (WSO).

Most of the critical weather elements discussed in Chapter 1 cannot currently be observed with the high degree of accuracy required in an endeavor as weather-sensitive as the space program, where small errors can produce catastrophic results. Although most public-service forecasters would be pleased to be correct 90 percent of the time in yes-no forecasts of precipitation, an accuracy that low for any of the weather elements critical for space flight could be devastating. The inescapable conclusion is that accuracies of about 99 percent or greater are needed when critical failures would result.

This requirement almost certainly dictates that decisions concerning weather-sensitive operations (1) will always be made as late as possible, (2) will be based largely upon observations at decision time, and (3) should err in favor of postponing the weather-sensitive activity if critical weather is even a slight possibility. Thus, aside from planning efforts that require forecasts for days or longer, the forms of weather information most important for space operations are diagnoses of existing conditions and very-short-term weather forecasts for periods of several hours or less.

As long as launches are infrequent and delays are tolerable, there is likely to be little pressure on the system. However, as launches become more frequent, weather-related delays will be less tolerable, and therefore improved capabilities for detection and forecasting of adverse weather are needed. How unfailingly can state-of-the-science instruments adequately detect critical weather elements? How well can state-of-the-science methods be used to forecast critical weather elements for 2-hour intervals?

This chapter gives an overview of (1) some of the existing measurement systems used at KSC (and, to a limited extent, at other sites), (2) other systems available for deployment, and (3) remaining needs for development of instrumentation to observe a few important meteorological parameters.

UPPER-AIR SOUNDINGS

High-resolution vertical profiles of wind speed and direction are needed to assess wind loads on the launch vehicle during launch and landing. The jimsphere balloon, tracked by radar, provides the greatest vertical resolution in measuring winds aloft. Data are normally obtained at 100-foot (30-m) intervals. Jimspheres provide the data used in assessing the wind loads prior to launches at KSC and Vandenberg.

Near the jet stream there can be large wind variations in less than 2 hours that could make prelaunch balloon-based soundings unrepresentative of launch conditions. Balloon-based wind profiles require about an hour to measure winds to 55,000-foot (17 km) altitudes, so it is impossible to obtain soundings at less than 1-hour intervals unless multiple tracking devices are available and several balloons are airborne at the same time.

Doppler wind profilers, which have been under development for a

decade, are in operation in a number of places worldwide. Although their vertical resolution is somewhat poorer than that of the jimsphere system, wind profilers can provide data at intervals as short as 30 seconds, if desired. There are plans to install a Doppler wind profiler at KSC before the end of 1988.

The wind profilers should be installed at and surrounding KSC in order to monitor important changes in the wind. Wind and wind shear data, as well as spectrum width of the profiler winds (which is related in part to turbulence within the beam), should be collected.

Once a suitable profiler data base is attained, the method of assessing launch wind load hazards to the shuttle should be examined. It should be determined if a network of wind profilers at and surrounding KSC could be used to obtain very-short-term forecasts of wind profiles at launch time through advection of wind field patterns across the network. A numerical model might be helpful in making these forecasts.

The type of wind data really needed during a launch is a profile along the launch trajectory. Neither balloons, which drift with the wind, nor profilers can provide this type of sounding. Aircraft are better suited to provide this type of information, but the present prelaunch aircraft are not instrumented to make accurate wind measurements. The program of prelaunch reconnaissance flights using T-38 and Shuttle Training Aircraft should be upgraded either by adding instrumentation to these aircraft or by using other available instrumented aircraft. Quantitative measurements should be made, over and upwind of KSC, of cloud electric fields, the types and sizes of precipitation, electric fields and Maxwell currents, winds, wind shears, and turbulence. A computerized data collection system should be used to facilitate the real-time collection and archiving of these data, and also to transmit the data to KSC forecasters for timely use. MSFC should explore the possibility of using these data as part of the JSC loads assessment program.

Thermodynamic soundings (temperature and relative humidity) are needed to obtain atmospheric density profiles during launches. These are obtained by balloon-based instruments, particularly the ground meteorological detector (GMD)-tracked radiosondes, and by rocketsondes. These systems should be assessed against the state-of-the-science technology, such as Loran-based balloon tracking systems. The latter have proven far superior to GMD systems for obtaining accurate wind speed profiles during field research experiments, especially during situations of strong winds aloft and in terms

of vertical resolution. Furthermore, the National Center for Atmospheric Research (NCAR) Cross-chain Loran Atmospheric Sounding System (CLASS) has been designed and demonstrated to operate nearly automatically, and would potentially provide better data with less manpower and cost than the present GMD system.

Remote soundings of temperature and humidity, obtained via satellite-based radiometric profiling, currently have vertical resolution that is too coarse for use in the space program. WSO should monitor the progress of research on these systems and be prepared to put them into use in the space program, should their resolution improve.

To obtain better information about spatial and temporal variations of the wind near KSC, NASA should establish a network of Doppler wind profilers and a program for enhanced aircraft observations using available NASA and U.S. Air Force aircraft.

BOUNDARY LAYER AND SURFACE WEATHER

Near-surface winds are important for landings, launches, and ground operations, and can be measured accurately and at very frequent intervals (1 minute or less) using automated weather stations. A system of this type, called WINDS (Weather Information Network Display System), is used at both KSC and Vandenberg, with sensors on towers from 54 to 500 feet at KSC and 12 to 300 feet at Vandenberg. Winds from these networks are available at 5-, 15-, or 30-minute intervals. Shorter intervals may be desired in the critical minutes before launch, when passage of a gust front (outflow from a distant thunderstorm) or the sea breeze front (moving in from sea) could cause dramatic changes of wind direction and speed.

The existing automated surface mesonetwork (28 stations) is a critical element in the observational program at KSC. It should be expanded to the west to cover the western portions of the KSC activity domain (and procurement of 20 additional stations is in progress), and to the east to include measurements over water, via buoys or platforms for routine operations and/or via ships during launch situations. The instrumentation should be expanded to include visual range transmissometers at the launch pads and the Shuttle landing field airstrip. The individual sites should be adjusted, if

necessary, to ensure that the observations are taken at uniform altitudes, with proper exposure and sheltering, and with uniform and well-maintained instrumentation.

A Doppler sodar (sonic detection and ranging) can be used to monitor the low-level (up to about 1 km) wind profile at 5-minute intervals except during precipitation. This instrument has better vertical resolution than the wind profiler, so Doppler sodars would be of value in augmenting the tower wind network. Such data would prove invaluable for dispersion forecasting and in providing information regarding other surface operations. A Doppler Acoustic Sounding System (DASS) is currently operated at Vandenberg.

The horizontal distribution of low-level winds provides important information for weather forecasting. Small-scale fronts and wind shift lines can escape detection if stations in a mesonetwork are more than several kilometers apart. Scanning Doppler weather radars and Doppler lidars can supply the type of spatial coverage needed to locate such wind shift lines. A NEXRAD Doppler radar is expected to be installed at Melbourne, Florida, about 25 miles south of KSC, in 1990.

Because a single Doppler radar can detect motion only along a radial, a network of at least two Doppler radars should be deployed at KSC in order to resolve total horizontal velocities. Unfortunately, the NEXRAD radar to be deployed at Melbourne within the next several years will not scan in a manner conducive to multiple Doppler radar studies in consort with another radar. NASA should acquire at least two dedicated Doppler radars, which would enable calculation of detailed patterns of winds in clouds and in the boundary layer. To make the wind calculations in real time would require the development of new dual-Doppler data processing and display software. In addition to horizontal mappings of velocity, cross-sections along the space vehicle flight path could also be constructed.

To obtain enhanced information about low-level winds and other weather elements, NASA should expand the areal coverage of the surface mesonetwork and include data platforms over the ocean. At least two dedicated Doppler radars should be installed in locations that optimize coverage over KSC to improve forecasts using higher resolution boundary layer data and to better relate the wind fields and reflectivity within clouds to the microphysical and electrical development. NASA should consider deploying Doppler sodars for monitoring the boundary layer.

PRECIPITATION

Showery precipitation often falls over areas of only a few square kilometers, and rain gauge networks are rarely dense enough to resolve this detail. Conventional (non-Doppler, incoherent) weather radar can be used to obtain high-resolution mappings of areas with precipitation. Forecasters use the horizontal and vertical shapes of the radar "echoes" and the intensity of the echoes to identify convective and stratiform precipitation. Satellite imagery can also be used to help identify convective clouds. However, neither radar nor satellites can unambiguously distinguish thunderstorms from other types of convective precipitation.

State-of-the-science weather radars provide digital data that can be processed by computerized software packages to derive additional useful products such as vertically integrated liquid water contents, cross sections of reflectivity at any desired angle, and animated imagery. The 30-year-old FPS-77 radar at Vandenberg is not digitized and provides the forecaster only with snapshot views at fixed azimuth or elevation angle. A radar should be deployed at Edwards AFB, and digital radars should be considered for both Vandenberg and Edwards.

The thermal tiles on the Space Shuttle are eroded by precipitation drops. However, there is a need for more detailed information relating drop size and concentration to the extent of the tile damage. Unfortunately, drop sizes cannot be measured using conventional radar. Surface-based disdrometers are typically used to measure raindrops reaching the ground, and an aircraft-mounted Knollenberg probe can be used to sample sizes of precipitation aloft. These types of instrumentation are not currently used in space operations, but should be.

A possible tool of the future is the multiparameter radar, which transmits at two wavelengths and with two polarities. Multiparameter radars can distinguish between snowflakes, raindrops, and hail, and between large drops and small drops. However, certain ambiguities exist, such as melting snowflakes. Additional research should be done to enable this tool to be utilized operationally.

To obtain data on cloud and precipitation types and sizes, airborne drop-size measuring instrumentation should be flown prior to Space Shuttle launches, and a multiparameter radar should be acquired.

LIGHTNING

During the summer at KSC there is an average of about six lightning strikes to ground per square mile each month. Until the last decade, it was extremely difficult to detect and locate lightning strikes on a real-time basis. Cloud-to-ground lightning strikes can now be successfully detected by using either magnetic direction-finding (Lightning Location and Protection (LLP)), omnidirectional broad-band time-of-arrival (TOA) antennae (Lightning Position and Tracking System (LPATS)), or by careful interpretation of electric field mill network data. (Other methods also exist, such as lightning-detection radar and lightning interferometers.) Lightning strikes are typically located with position accuracies of 2 km or better by triangulation. An LLP system is in operation at KSC; it should be improved by periodically checking the site correction factors and the antenna alignments.

Two larger lightning detection networks cover the KSC area: a network of LLP direction finders operated by the State University of New York at Albany and the Florida LPATS network of broad-band TOA receivers. Displays of these data should be added to the KSC weather office. Data from the SUNY Albany system showed the movement of an area of considerable cloud-to-ground lightning activity toward KSC from the west prior to the Atlas-Centaur 67 accident, as shown in Figure 4. Had these data been available in the KSC weather office, it is likely that the launch would have been postponed, averting the accident.

At KSC, at present, in-cloud and cloud-to-cloud lightning discharges are difficult to detect. These occurrences can be inferred from data provided by the Launch Pad Lightning Warning System (LPLWS), a 30-station network of field mills that is designed to detect electrified clouds. Because the LPLWS is the only network of its kind in the world, few meteorologists have been exposed to these data for use in real-time weather analysis and forecasting. Persons who would typically provide forecaster training are not usually well versed in this tool, and those familiar with field mill network interpretation are usually more adept at using it in a research rather than an operational environment.

The LPLWS is currently being upgraded. The sensors should be improved, and the sites should be carefully evaluated to identify any local obstructions or sources of contamination, and obstructions should be removed or sites relocated, if necessary. The network should be expanded to the west and to the east, including over-water

FIGURE 4 State University of New York (SUNY) at Albany display of LLP-detected cloud-to-ground lightning prior to the Atlas-Centaur 67 launch. In the 3 hours prior to launch, lightning activity progressed steadily across Florida toward KSC. (Courtesy of R. Orville, State University of New York at Albany.)

sites. The equipment should be carefully calibrated and certified for operational use, and the observations included in the list of weather criteria for launch (and landing).

In-cloud and cloud-to-cloud lightning can also be detected by using networks of (1) HF or VHF time-of-arrival receivers or (2) HF or VHF lightning interferometers. A system (LDAR) of the former type was previously operated at KSC but abandoned. A new system of this type should be built.

The National Aeronautics and Space Administration should make improvements to the existing LLP and LPLWS systems and obtain displays of other lightning detection networks in the area, in order to improve detection of lightning and electric fields. A new system should be built to detect lightning in and between clouds aloft.

CLOUD ELECTRIC FIELDS

Clouds, such as thunderstorm anvils, stratiform thunderstorm anvils, stratiform clouds, and shallow convective clouds, often do not produce lightning but do contain high electric fields. The threat of triggered lightning from these clouds may be the most difficult weather hazard to detect and forecast. Surface electric fields do not always reveal electric fields aloft or charge centers in the upper portions of clouds, because of the presence of intervening (or screening) charged layers. Airborne electric field mill systems, such as those formerly used on the NASA F106-B research aircraft, should be used to accurately characterize the electrical environment aloft.

Much of the data collection and research on the subject of triggered lightning has been sponsored by KSC, so that the center's triggered lightning research is state-of-the-science within the atmospheric electricity community. Additional efforts are needed to add companion meteorological data (such as radar data, surface mesonetwork and tower data, satellite data, and sounding data) to the triggered lightning data base for possible forecasting applications and to provide training to operational forecasters concerning the use of field mill network data. Airborne measurements using field mills represent an important contribution to better defining the potential for induced lightning.

The new launch criteria, designed to avoid any possibility of triggered lightning, may have become overly conservative with regard to cloud electric fields. To address this issue, one or more instrumented aircraft should be flown on frequent occasions in order to develop a climatological data base regarding electric fields and Maxwell currents in "dead" or detached anvils and anvils from distant thunderstorms. Data should also be collected in other types of cloud near the freezing level.

Triggered lightning studies should be continued, with additional efforts to collect companion meteorological data sets. Airborne electric field measurements should be collected to enhance studies of the threat of triggered lightning.

OTHER WEATHER ELEMENTS

Dangerous icing conditions will result if a vehicle encounters supercooled (i.e., liquid at subfreezing temperatures) cloud and precipitation drops. Owing to the poor spatial coverage of rawinsonde

data and since conventional weather radar cannot distinguish between precipitation sizes or types, regions conducive to aircraft icing are very difficult to detect. Pilot reports are the main source of information. Multiparameter radar, combined with temperature profiles, might prove useful for detecting and avoiding freezing rain. Cloud radars (wavelength of approximately 3 mm), which detect cloud-sized particles, may prove useful in supercooled cloud detection, if used with sounding data.

Clear-air turbulence, which arises within layers of large vertical wind shear, is very hard to detect. It is most commonly detected and reported by pilots. Some information regarding shears and hence the possibility of turbulence can be derived from the spectrum width of Doppler radar data, both from scanning Doppler weather radar and from Doppler radar wind profilers. Much work remains to be done, however, in calibrating the spectrum width values against the incidence of turbulence. Satellite imagery can also often be used to alert forecasters to areas where turbulence is likely.

Trained weather observers can also provide valuable data to the weather forecaster. An observer has the unique ability to assimilate audible and visual data in a manner that is better than most instruments. To obtain quality information, the observers must be trained to identify the specific conditions that may be conducive to weather hazards such as triggered lightning. At KSC, the weather office has no windows, and forecasters cannot see outside without climbing to the roof. It would be desirable to move the forecasting operations to a room with a window or to make a window in the room currently used, so that observers could more easily monitor rapidly changing atmospheric conditions.

Trained and reliable observers and adequate facilities are needed at all sites overseas and in the United States. The panel does not feel comfortable with past arrangements for obtaining weather observations at overseas landing sites.

The National Aeronautics and Space Administration should ascertain that launch and landing sites are provided with skilled observers and necessary measurement systems. NASA should monitor the achievements in observation technology and deploy useful new instrumentation expediently.

4
Analysis and Forecasting Systems

The previous chapter has pointed out that there are many types of observing platforms currently in use at KSC and other launch and landing sites, and that improvements and additional platforms are required. In a real-time operational setting, however, new and improved data do not necessarily translate into improved diagnoses and forecasts. If data from each source were considered independently, the correct prognosis might become progressively blurred. This is especially true because of the complexity of the mesoscale weather systems that affect KSC, which may be of such small scale that individual measurement systems are only able to give a skeletal picture of the phenomenon. In this situation, the key to successful diagnosis and forecasting lies in the joint use of data from many different sources, each providing a bit of information not treated by the others, to obtain a clear understanding of the weather situation. The skill needed to perform this mental assimilation is not gained quickly or easily. It requires intelligent, experienced, and dedicated personnel; training; practice; and the proper system (hardware and software) with which to examine the data. These topics will be treated in this chapter.

DATA ACQUISITION AND DISPLAY

In order to perform timely analyses and diagnoses, the AWS forecasters servicing KSC and the NWS forecasters at JSC make use of a computerized interactive analysis and display system called MIDDS (Meteorological Interactive Data Display System). This system is capable of displaying large-scale diagnostic and prognostic data, as well as zooming into the observational networks on the local scale surrounding KSC. This powerful system can meet the hardware and software needs of the mesoscale forecaster if it is used optimally.

One strength of MIDDS lies in its graphical overlay capability, which fosters the joint use of data in the manner discussed above. This enables a clearer depiction of the structure of the weather systems and an improved understanding of the interrelationships between the different scales of motion and different data fields, such as between changes in the electric field and the movement and development of radar echoes. Another invaluable feature is the looping capability, which facilitates the use of prognoses based on extrapolating the movement and evolution of the weather systems.

To be most effective, however, all types of data must be accessible on the MIDDS system. At the time of the panel's visit to KSC, electric field mill and other data were not incorporated into the MIDDS data base and had to be examined on a stand-alone display. Future plans call for all data sets to be available on MIDDS; these plans need to be promptly executed. All sources of satellite data, including NOAA and DMSP polar orbiting satellites, as well as all channels (e.g., visible, all infrared and near infrared, and microwave channels) should be received.

> **The Weather Support Office should expedite plans to incorporate all data sets on MIDDS and promote the joint display of disparate data sets.**

Improvements in analysis and forecasting procedures can be attained almost immediately through better use of existing data: (1) A series of lectures and training sessions should be scheduled to bring the staffs at KSC and JSC up to date regarding the latest techniques and procedures in interpreting and using satellite imagery in synoptic-scale diagnosis. Special emphasis should be placed on the use of water vapor imagery. (2) A routine procedure should be established requiring reanalysis of surface and selected upper-air charts at more contour intervals and with less smoothing than those received from the National Meteorological Center. (3) A MIDDS program

should be written to generate vertical time-sections of upper-air and surface data and, ultimately, profiler data. This tool can help to detect moderate-scale weather systems and thereby enhance analyses and prognoses. (4) Immediate benefits can be obtained through a program of inviting visiting scientists with operational experience to interact with operational forecasters.

Because the types of weather events that cause disasters are rare, it would be valuable to let a computer maintain a continuous lookout for telltale signals of a potentially dangerous phenomenon. Human forecasters cannot watch the LLP display 24 hours per day, 365 days per year, yet a 5-minute delay in detecting the first lightning discharge on an otherwise quiet day could cost lives. An alert system that is triggered whenever a critical weather element exceeds a hazard threshold is needed. For example, an alert could be triggered when the LLP lightning detection system detects a cloud-to-ground discharge occurring within a certain distance of the launch pad or other weather-sensitive area. Other alerts could be triggered by changes in or large values of electric field, by excessive low-level wind shear, by strong low-level moisture convergence, and so on.

Critical observations or parameters derived from analyses should be monitored by computer to allow continuous surveillance between periods of human monitoring.

LOCAL OBJECTIVE ANALYSES

The abundant and diverse types of data may confuse weather personnel unless steps are taken to assimilate and consistently analyze data from all sources and transform them into high-resolution gridded fields of understandable variables.

Techniques to assimilate and analyze these data should be automated so that the forecaster need only consider fields analyzed from gridded data, such as the three-dimensional vector wind. Similarly, observations of temperature and moisture from satellites can be combined with surface and mesonet observations to provide structure at very fine scales.

By using a gridded format, a number of specific space-flight-oriented products can be generated, and nowcasting can be greatly enhanced. The detailed analyses can also serve as first-guess fields in initialization of mesoscale numerical models. With four-dimensional data assimilation techniques, the model equations themselves could

form the framework of the analysis algorithm, further improving the process.

There is a need to develop local (KSC) analysis systems that incorporate all data sources and provide high-resolution gridded fields appropriate for forecaster and numerical model use.

INTERACTIVE FORECAST SYSTEMS

There is a need to develop aids to help forecasters avoid being overwhelmed and to help them systematically consider only the data appropriate for use in making various forecast decisions during differing weather situations. One such aid needed is classified as a "decision tree," a stepwise procedure which enables the forecaster to consider all pertinent data when being called on to forecast a given condition or parameter. With the versatility of MIDDS, such decision trees should be developed as dynamic tools that permit interactions with the user. They should be developed to incorporate not only observations and conceptual models, but also output from nested mesoscale numerical prediction models, objective forecast studies, and objective and subjective evaluations of forecasters.

The need to understand and forecast cloud electrical development is particularly urgent. Since existing thunderstorms can be monitored with the field mill, radar, and lightning detection networks, the three problems that require attention are (1) the onset of lightning in developing thunderstorms, (2) the continuation of lightning in decaying thunderstorms or detached anvils, and (3) the threat of triggered lightning in convective and nonconvective clouds.

Although these problems need longer-term applied research with new measurement systems, some gains could be obtained through subjective and statistical studies of available data sets. The existing yes/no data from triggered lightning studies at KSC, for example, could be used together with parameters such as electric field, cloud base height, height of the freezing level, cloud top infrared temperature (or inferred height), distance from radar echo, surface convergence/divergence values, and so on, to develop decision trees for forecasting triggered lightning. Decision trees should also be developed for each of the other critical weather variables discussed in Chapters 1 and 3.

Another approach to developing forecaster aids is through use of expert systems or "artificial intelligence" (AI) techniques. In some ways these approaches are similar to decision trees, but with heavier

emphasis on the computer as opposed to human interaction. This technique also might be worth applying to available electrified and triggered lightning data and various accompanying data sets.

The panel believes that the artificial intelligence research going on at KSC is addressing forecasting problems in a manner that is almost as if it is starting "from scratch" and that it is not likely to yield state-of-the-science forecasting techniques. The panel suggests that AI research be focused toward specific problems such as determining how to optimally combine measurements of the types listed above to yield accurate short-term forecasts of the threats from natural and triggered lightning.

There is an urgent need for the development of interactive "decision trees" and computer-aided decision-making methods to help the forecaster make most efficient use of data in reaching decisions, particularly in forecasting thunderstorm formation and natural and triggered lightning.

MESOSCALE FORECAST MODELS

Mesoscale forecast models offer the potential for dramatic enhancements in future forecast accuracy. Mesoscale models have successfully simulated many important mesoscale circulations and storm systems. New nested mesoscale models are becoming available that are nonhydrostatic and contain embedded fine mesh grids that provide enhanced resolution where small-scale structures are evolving. With the help of a local analysis system, discussed in the previous section, high-resolution analyses could be used to initialize these forecast models. Model studies have demonstrated that, in many cases, the forcing influences that generate mesoscale weather systems originate in the larger-scale environment and are therefore predictable from coarser resolution initial data.

Further applied research and development will be required to realize the anticipated improvements in forecast accuracy and to adapt these models to an operational environment. Numerous issues, such as data assimilation, model initialization, and parameterized physics can be refined to improve the accuracy of mesoscale forecast models. With the installation of a wind profiler network, the KSC environment would be ideally suited as a test bed for mesoscale model development and testing. NASA's weather-support should take an active role in encouraging this research and work with the modeling projects to develop products that address KSC forecasting needs.

The National Aeronautics and Space Administration and other participants in the space program should take an active role in encouraging development of numerical models dealing with weather elements crucial to the space program.

5
Implementation of Applied Research, Technology Transfer and Training, and Experimental Forecasting

Many suggestions and recommendations have been made for improving existing instrumentation and deploying new equipment for various types of applied research that will enhance weather support for space flight. In addition, outside of the space program there will continue to be new developments that could prove useful for meteorological support of space flight. These future weather research and technique development programs offer the opportunity to enhance substantially our ability to observe, understand, and thereby predict the weather processes that are important for KSC operations. Several factors are currently contributing to an increased emphasis on mesoscale weather systems that, if properly coordinated, could be of great benefit to KSC forecasting. Research in mesoscale meteorology is currently a very high national priority. This is reflected in the growth of the National STORM Program* and confirmed by the recent NSF-UCAR Long-Range Planning Committee Report,** which recommended a Mesoscale Meteorology Initiative as one of four major community science initiatives. Mesoscale meteorology has advanced

* *The National STORM Program, STORM Central Phase, Preliminary Program Design*, May 1984, NCAR, Boulder, Colorado.

** *The Atmospheric Sciences: A Vision for 1989-1994.* Report of the NSF-UCAR Long-Range Planning Commission, July 1, 1987, J. Dutton, Chairman, 48 pp. Available from UCAR, Boulder, Colorado.

in sophistication to the degree that the field can now contribute substantially to improved observation and prediction of local weather features. Central Florida experiences many economically important and scientifically interesting weather phenomena that are attracting new research initiatives in the area. The proposed Florida Area Mesoscale Experiment exemplifies the research interest in this area.

The prospects for advances in weather forecasting at KSC are enhanced by a unique confluence of interest, need, and opportunity. Substantial resources are already being directed toward weather phenomena in the vicinity of KSC; the challenge is to focus and coordinate these efforts to solve the most important weather forecasting problems.

APPLIED RESEARCH AND FORECAST FACILITY (ARFF)

As new advances in observing and understanding weather systems are achieved, projects must be initiated to translate the advances into new and better forecast techniques that are then transferred quickly and effectively to operational use. Forecasters can gain additional skills through assimilating these techniques into their individual repertoires. However, it is difficult to familiarize forecasters with new techniques while they have ongoing operational duties. Rotating forecasters through frequent training programs is one way of providing technology transfer. Another is by establishing an experimental or simulated forecast environment where forecasters can practice and gain working exposure to experimental activities on a daily basis. In talking with weather support personnel, the panel perceived a general recognition of the efficacy of these concepts, but heard widely differing views on how they should be achieved. The panel is convinced that significant improvement in weather support will require new approaches, increased cooperation, and a larger commitment of resources.

Efforts to improve weather analysis and forecasting capabilities can be greatly facilitated by a group that is charged with monitoring the research advancements of the scientific community and applying the results to improve weather support for the space program. The need for such a group has been recognized by several agencies, and several operational units within NOAA, including the Spaceflight Meteorology Group at JSC, already have positions designated for these functions. However, the three-person NOAA effort at JSC is

below a critically effective staffing level, is not sufficiently broad in scope, and is not located at KSC where it would be most effective.

The panel believes that the creation of an Applied Research and Forecast Facility (ARFF) at KSC would provide an ideal focus for future applications research and the development of new forecasting techniques. The ARFF should have responsibility for operating and evaluating prototype observing systems, developing and evaluating new forecast tools and techniques, and contributing to forecaster training and forecast verification. For such a facility to be successful, it must also have the active involvement of the research and operational communities.

An Applied Research and Forecasting Facility (ARFF) should be established at KSC to promote the development and application of new techniques to improve forecasting for space operations.

Interaction Between ARFF, Operational Units, and Applied Research Groups

The Applied Research and Forecasting Facility should be a mission-oriented interagency facility that is managed by NASA through the newly created Weather Support Office (WSO). Its director should be an atmospheric scientist who has experience in both operational and research meteorology. The staff would ideally include Air Force, NASA, and NOAA personnel, with term and visitor appointments from throughout the atmospheric sciences to provide a further infusion of both research and operational talents. This facility could be created largely from existing resources by streamlining redundant activities and reorienting and reassembling these resources.

The success of the ARFF would depend critically on its developing close working ties with the operational forecast units and establishing an attitude of team effort and mutual support. To promote these relationships, it is vital to have ARFF co-located with the Cape Canaveral Forecast Facility servicing KSC and to rotate operational staff between them regularly. Joint weather discussions should be conducted on a daily basis, as a vehicle to stimulate interaction.

Clearly, there must be only one source of operational forecasts at KSC, and this responsibility should remain with the AWS forecast team. However, by operating in close proximity, the operational and experimental units can develop a cooperative relationship, where the

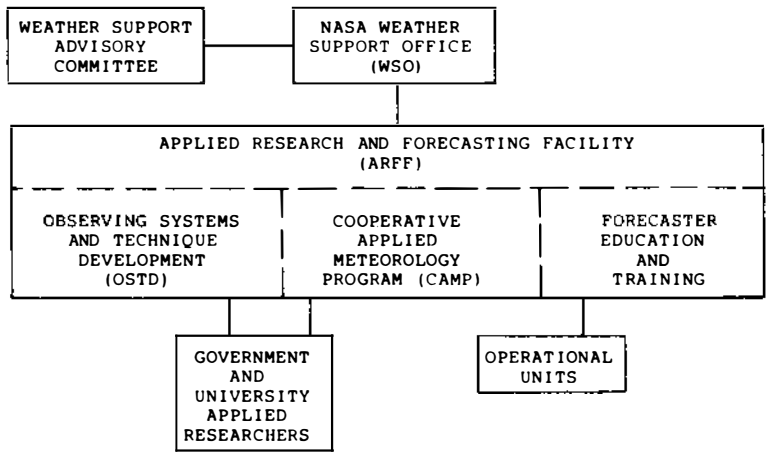

FIGURE 5 Schematic diagram of the Applied Research and Forecasting Facility (ARFF), its components, and its interactions with other units and agencies.

ARFF scientists and forecasters know the forecast requirements, and the on-line forecasters are receptive to new approaches. Although co-located with the Cape Canaveral Forecast Facility, the ARFF would serve not only those AWS forecasters, but also the AWS forecasters from other detachments and the NOAA forecasters from JSC. Operational forecasters and applied researchers should spend time at ARFF, rotating into the ARFF at regular intervals.

Figure 5 is a schematic diagram of the components of the ARFF and the routes of interaction between ARFF and other groups. As shown in the diagram, ARFF can be divided functionally into three sections: an Observing Systems and Technique Development (OSTD) Program, a Cooperative Applied Meteorology Program (CAMP), and a Forecaster Education and Training Program. A Weather Support Advisory Committee should assist the WSO in reviewing plans for, and progress of, the ARFF. Each of these components is discussed in a separate section below.

The Applied Research and Forecasting Facility should promote interaction between applied researchers and operational forecasters. To effectively reach forecasters, ARFF should be established adjacent to the operational forecast office at the Cape Canaveral Forecast Facility servicing KSC, and forecasters from KSC and other units should be assigned tours of

duty within ARFF. To provide researcher interaction, government and university researchers should also be encouraged to spend time at ARFF.

Applied Research for Weather Support

Many applied research projects have been recommended in this report. Some projects require new equipment that is ready for installation into an operational environment, but they will still require evaluation of the data on a real-time basis to identify and optimize its utility in the local environment. For example, after a NEXRAD radar is installed at Melbourne, Florida, it is likely that the "operational" hail-detection algorithm (designed for the Midwest) will need to be modified empirically to account for the reduced frequency of hail reaching the ground in Florida, where the melting level is normally higher. This type of project is best suited for real-time, in situ investigation. The OSTD in ARFF will conduct these evaluations and be the conduit for improved weather support.

Most research projects will require substantial development efforts before products will be ready for testing in the operational environment. Some of these projects can be done outside of KSC by government and university researchers or by private contractors. Regardless of where the research is to be performed, two items are essential: a prioritized schedule of applied research to be performed and a budget with which to sponsor it. The WSO, with the advice of the Weather Support Advisory Committee, should provide the schedule; WSO should provide the budget.

The present level of funding at KSC to support all the necessary research initiatives is inadequate. However, even with additional funding, the potential for enhancing research advancements cannot be realized without a restructuring of research funding channels at KSC. The current funding support is fractionated among a number of groups, with little overall coordination, and without a clear focus on the most important problems. Although KSC personnel are dedicated and advances have been made, there appears to be no internal core of expertise qualified to promote or critically evaluate most of the research initiatives.

The panel advocates a well-funded, applied weather research program, operating within ARFF, that heavily emphasizes observing systems and development of forecasting techniques and that is coordinated by the WSO. The ARFF should contain a strong internal

core of scientific expertise, capable of assessing research proposals and results. Research grants should be made through the facility in support of priorities and directions specified in a comprehensive long-range research plan. Outside peer review of research proposals should be part of the evaulation process.

Applied research should be consolidated within the ARFF at KSC. ARFF should monitor advances in all areas of atmospheric science to identify new technology that should be deployed in support of the space program, and it should commission studies of this type through a research grants program.

OBSERVING SYSTEMS AND TECHNIQUE DEVELOPMENT (OSTD)

A central function of the ARFF would be to evaluate new observing systems and analysis techniques, and to develop and test new procedures for operational forecasting. These duties are broad in scope and would encompass many of the activities conducted both in NWS Experimental Forecast Centers and the NOAA Program for Regional Observing and Forecasting Services (PROFS). The ARFF would also have responsibility for monitoring the development of data assimilation systems and mesoscale models and for promoting their application in forecasting mesoscale weather systems in the vicinty of KSC.

The facility should compile good climatological and weather data bases in the vicinity of KSC for use in evaluating new forecast techniques and to aid in assessing the impact of changes in weather-related operating criteria. The climatological data required include variables other than those normally encountered (maximum and minimum temperatures, and so on), such as the critical weather elements included in launch and landing weather rules.

In addition, the ARFF should have responsibility for monitoring operational forecasts and assessing the accuracy of forecasts of parameters identified within the launch and landing weather criteria. This activity is required since accurate and meaningful stratification of verification statistics is an important part of technique assessment that can help eliminate forecaster biases and promote forecaster improvement.

The Applied Research and Forecasting Facility should be

assigned responsibility for testing and evaluating prototype observing systems, developing improved forecast techniques, verifying forecasts, and compiling climatological data.

FORECASTER EDUCATION AND TRAINING

The education and training of operational forecasters is particularly important, especially in view of the special requirements placed on forecasts for launch and landing operations. Another factor is that forecasters rotate through the AWS, and new forecasters must continually be trained. The Air Force has recently initiated several organizational changes to increase the experience level and improve the continuity of forecasters. This unit has developed a professionalism and a strong commitment to quality that provides an ideal base on which to build.

The Air Force weather office conducts ongoing forecast training activities that should be continued. In addition, the ARFF should have responsibility for augmenting this training, particularly in the understanding of weather situations specific to KSC and in the use of specialized forecast techniques. Training can take place through several media; video tapes, simulated forecasts for launch/landing/recovery operations, lectures, and map discussions are all possible methods. Real-time experience is also recognized as one of the most valuable training mechanisms. Rotating operational forecasters through the ARFF would serve to accelerate the learning process in an environment where daily forecast situations can be evaluated with ARFF staff without the pressure of on-line responsibility. In addition, as new tools and techniques become available, there should be a formal transfer of knowledge, with adequate accompanying documentation.

Part of the ARFF function should be to establish education and training procedures for operational forecasting.

COOPERATIVE APPLIED METEOROLOGY PROGRAM (CAMP)

Advancements in weather research that support space operations can benefit greatly from the organization of field programs and stimulation of relevant research in the university community. Government agencies have found that cooperative programs with the university community are an effective mechanism for administering

programs where flexibility is important in maintaining an "edge-of-the-art capability." The panel believes that a Cooperative Applied Meteorology Program (CAMP) with formal university involvement would provide an ideal augmentation of the ARFF. CAMP would coordinate field programs and other research beneficial to operational weather problems, administer a research grants program, and promote strong scientific interactions with the permanent ARFF staff. Establishing this strong university involvement could also serve to attract funding from other agencies and other offices in NASA that support atmospheric research.

Periodically, it is necessary to bring together a concentration of special equipment, facilities, and talent to achieve breakthroughs in the understanding of specific weather phenomena. These field programs will be particularly important in advancing our knowledge of electrical and microphysical processes in convective and nonconvective clouds in the KSC environment, and in determining the predictability of convection from the data provided by new observing systems.

Making state-of-the-art observing systems available to the research community will enhance interest that is already strongly in evidence. The proposed Florida Area Mesoscale Experiment (FAME) plans a major field program in central Florida in 1990. The observing systems and research objectives outlined in this report, if implemented, should be highly compatible with the interests of any group interested in researching Florida weather. The facility should become the prototype suggested in the letter in Appendix A.

Equipment upgrades planned by the National Weather Service are likely to yield better information on weather systems affecting KSC. A NWS NEXRAD radar is planned for installation at Melbourne, Florida; the capabilities and limitations of this radar in contributing to an advanced observing network must be assessed. The NWS also plans to deploy a network of wind profilers over the central United States. With research wind profilers already working in Pennsylvania (Pennsylvania State University) and soon to be installed in Florida (NASA) and Massachusetts (AFGL), there will be a strong desire by the atmospheric science community to deploy wind profilers over the remainder of the East to form a continuous network from the Rockies to the Atlantic. Several universities are already preparing a joint proposal for a Southeast Profiler Network.

These and other initiatives should be scrutinized and, if appropriate, coordinated by CAMP as part of a concerted effort to improve

the understanding and prediction of important weather features in central Florida.

A Cooperative Applied Meteorology Program (CAMP) should be established within the ARFF to promote the participation of university and mission-agency scientists in field programs advancing weather research and forecasting in the vicinity of KSC or at other launch and recovery sites.

The advanced observing systems, comprehensive data sets, and new techniques developed will provide an attractive facility for research scientists, operational meteorologists, and graduate students to visit, where they can interact with ongoing activities. These visitors would provide a continuous influx of new ideas and approaches and would become aware of important weather phenomena in the KSC area that might stimulate further research on these topics in the scientific community. The University Corporation for Atmospheric Research (UCAR) might be the ideal organization to administer this program, because it already has experience in the types of activities recommended for CAMP. UCAR has strong university connections, has a Naval Environmental Prediction and Research Facility (NEPRF)/National Meteorological Center (NMC) Visiting Scientist Program (VSP), and is in an excellent position to monitor closely related programs going on in NCAR.

A strong visiting scientist program should be established within CAMP to attract research and operational talents from throughout the nation that contribute to the goals of the ARFF, within the guidelines of WSO.

WEATHER SUPPORT ADVISORY COMMITTEE

To ensure that the director of the WSO and the director of the ARFF receive unbiased views and the best technical advice available as to opportunities and directions, a Weather Support Advisory Committee should be established by WSO. The committee should review plans and give advice on future directions. The advisory committee should be charged with ensuring that NASA has and maintains the best and most cost-effective weather support that can be provided. As part of its duties, the advisory committee should monitor the operations of the ARFF and its research grants program.

As has been noted throughout this report, serious organizational

and coordination problems exist in the current weather support system. One mechanism for ensuring coordination among independent agencies would be participation of high-level personnel from the various agencies in the Weather Support Advisory Committee. Thus it is recommended that the committee consist of members from NASA, Air Force, NOAA, and academia. The director of the WSO should be an ex-officio member and should call and host the meetings.

The Weather Support Office should form a Weather Support Advisory Committee to periodically assess for the WSO the organizational and technical issues that affect weather support for NASA's space operations.

APPENDIXES

Appendix A
Letter from NASA to the Academy Requesting Establishment of Panel

NASA

National Aeronautics and
Space Administration

Washington, D C
20546

NOV 17 [illegible]

Reply to Attn of MO

Dr. Frank Press
President
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Dr. Press:

NASA requests the assistance of the National Academy of Sciences in our endeavor to improve the National Space Transportation System (NSTS) Weather Forecasting System. We require your atmospheric science expertise to identify how NASA can instrument the Kennedy Space Center (KSC) as a prototype weather nowcasting facility.

On November 12, 1986, my staff discussed this request with Dr. John Perry of the National Research Council. Dr. Perry suggested we proceed with a formal request for the Academy's services.

Our objective is to encourage the research community to sponsor atmospheric activities utilizing KSC as a test ground for the application of state-of-the-science meteorological nowcasting techniques and technology.

Resumption of routine Shuttle landings at KSC is in part dependent upon improving our current weather support system to provide a high level of confidence in a 90-minute prelanding forecast. The dynamic atmospheric conditions manifested at KSC, combined with the Space Shuttle sensitivity to a range of environmental parameters (thunderstorms, lightning, turbulence), make this a very challenging requirement.

The Office of Space Flight is in the process of developing a 5-Year NSTS Weather Forecasting Improvement Plan, consistent with the recommendations of the Presidential Commission on the Space Shuttle Challenger Accident. Development of KSC as a prototype nowcasting facility is a cornerstone of that plan.

We would like you to define the improvements necessary to create such a prototype system and provide NASA with an implementation plan.

We look forward to working with the Academy to develop a state-of-the-science weather forecasting capability for the Space Shuttle. Please contact Karen Poniatowski (FTS 453-2520) of my staff for any clarification.

Sincerely,

Richard H. Truly
Associate Administrator
for Space Flight

Appendix B
List of Attendees and Participants

A. Aldrich, NASA/Hdqrs
V. Aquino, AWS/Hdqrs
J. Arnold, NASA/MSFC
L. Austin, NASA/JSC
R. Babcock, AWS/Vandenberg
J. Bates, NASA/JSC
A. Beller, NASA/KSC
R. Bentti, NASA/KSC
K. Bobko, NASA/JSC
T. Boles, AWS/JSC
W. Boyd, ESMC
N. Buss, AWS/KSC
G. Chapman, AWS/Hdqrs
G. Coen, NASA/JSC
R. Crippen, NASA/KSC
J. Crowley, AWS/JSC
J. Ernst, NASA/Hdqrs
G. Fichtl, NASA/Hdqrs
J. Friday, NOAA/NWS
K. Glover, AFGL
M. Henderson, NASA/JSC
H. Herring, Pan Am/ESMC
K. Hill, NASA/MSFC
R. Holle, NOAA/ERL
W. Jafferis, NASA/KSC
G. Krier, NASA/Hdqrs
R. Lavoie, NOAA/NWS
C. Lennon, NASA/KSC
R. Lewis, AWS/JSC
H. Loden, NASA/JSC
J. Madura, AWS/PAFB
J. Mahon, NASA/Hdqrs
L. Maier, CSG/KSC
J. McBrearty, NASA/KSC
P. McCalman, NASA/KSC
R. McClatchey, AFGL
M. McCulley, NASA/JSC
R. McPherson, NOAA/NMC
J. Meyer, NASA/KSC
C. Morrill, NOAA/JSC
T. Myers, AWS/Edwards
W. Newman, NASA/KSC
S. Nichols, NASA/Hdqrs
J. Nicholson, NASA/KSC
P. Nostrand, AWS/JSC
L. Penn, NASA/JSC

A. Peterson, NASA/Hdqrs
K. Poniatowski, NASA/Hdqrs
D. Puddy, NASA/Hdqrs
G. Rigdon, NOAA/JSC
T. Robertson, AWS/JSC
D. Rotzoll, NOAA/JSC
R. Sieck, NASA/KSC
J. Smedley, NASA/KSC
O. Smith, MSFC/CSC
J. Stahman, ESMC
T. Strange, AWS/KSC
E. Tarkington, NASA/JSC
J. Theon, NASA/Hdqrs
R. Thorson, NASA/JSC
C. Tracy, AWS/Andrews AFB
R. Truly, NASA/Hdqrs
M. Uman, U. of Florida
R. Wesenberg, NASA/KSC
M. Wheeler, AWS/CCAFS
V. Whitehead, NASA/JSC
T. Wilfong, AWS/CCAFS
G. Wilson, NASA/MSFC
R. Wojtasinski, NASA/KSC
J. Womack, NASA/KSC
J. Young, NASA/JSC

Appendix C
Recommendations from the Report of the Space Shuttle Weather Forecasting Advisory Panel to the NASA Associate Administrator for Space Flight, October 1986

1. The National Aeronautics and Space Administration should establish a Weather Support Office at the top level of Shuttle operations to plan, organize, focus, and direct the activities related to Space Shuttle weather support. The head of this office should be a senior atmospheric scientist or a senior technical manager with a strong operations background, who is knowledgeable about operational weather forecasting and research and development and who commands respect in the meteorological and NASA communities. Under the optimum organizational structure, the head of this office would have line authority for all Shuttle weather support personnel and programs. However, both the present and planned Shuttle launching ranges are operated by the Air Force to meet both Shuttle and additional requirements, and the Shuttle itself is operated by NASA. The panel recognizes that the optimum arrangement may be impossible to implement in practice and recommends that responsibility and authority for programs and personnel be consolidated in the Shuttle Weather Support Office to the extent possible.

2. There must be a small, highly qualified, well-trained, and dedicated team of forecasters who provide weather support for Shuttle operations. These forecasters should be willing to be an integral part of the Shuttle team and remain so for extended periods (5 to 10 years). Steps should be taken to ensure their continuity and devotion to the task (by grade and/or salary adjustments or other incentives).

3. To ensure that this team has the very latest research results and tools available and is trained to use these tools effectively, the head of the Weather Support Office should expand Techniques Transition Units at each operational site. These units should consist of one or two highly competent applied meteorologists and one or more computer specialists to act as an interface between the research and development community and the Shuttle forecast team.

4. There should be a standing advisory panel of experts to assist the Weather Support Office in charting its course, setting its priorities, and aiding in contacts with the Shuttle Program Office to secure continued support and visibility within NASA for the Space Shuttle weather effort.

5. The Meteorological Interactive Data Display System (MIDDS) can depict weather situations on a global basis. It is thus a key ingredient in forecasting and in communications of potential hazards to decision makers. The system needs to be developed at Johnson Space Center (JSC), and eventually Edwards Air Force Base (EAFB) and Vandenberg Air Force Base (VAFB). At each site having weather support responsibilities, MIDDS must be maintained and periodically upgraded to ensure that it represents the state of the art in rapid data access, analysis, and display capabilities.

6. The Doppler radar requirement to aid in the detection and observation of weather developments should rely on the NEXRAD facility, which will be installed and operated by the National Weather Service near KSC. Research on the processing and application of Doppler radar data should precede the completion of that installation to ensure that the data can be utilized promptly.

7. The models that are used for Space Shuttle wind-loading calculations need to be reexamined in view of the availability of ground-based remote wind profilers and their planned installation at KSC. Because the panel was unable to obtain access to the relevant computer algorithms, it is not possible to comment here concerning the adequate accuracy and resolution of these profilers for wind load assessments. A thorough study of methods and models for short-range wind forecasting should be undertaken with these and other technological advances under consideration, in view of the rapid wind profile changes under way preceding the *Challenger* launch. Rapid wind profile changes are undoubtedly common under many other weather situations.

8. The mesonetwork at KSC needs quality-control review and

probable augmentation for short-range wind and convective activity forecasts.

9. At KSC, airborne instrumentation is required to quantify the precipitation sizes that are observed over the launch site prior to launch to determine whether the precipitation may pose a threat to the orbiter thermal protection system.

10. A thorough study should be made of the available subsynoptic and mesoscale models to provide guidance to the Shuttle forecast team. Specific models should be selected and developed in parallel to ongoing operations. The use of such models as forecasting aids may have near-term payoff.

11. Research on artificial intelligence (AI) at KSC should be continued at a modestly supported research level until it can be shown to have real promise for the Shuttle forecast problem. Before investing significant resources in AI, it would be advisable to wait until some other group or agency has shown that this tool has potential for a similar type of forecast environment.

Appendix D
Proposed Weather Factors Governing Launch Commit Criteria and Flight Rules

Shuttle Launch Commit Criteria and Background

JSC-16007

Sec. 1.4

Weather Guidelines/Rules

LCC RULE: AMBIENT TEMPERATURE RESTRICTIONS

A. PRIOR TO EXTERNAL TANK CRYOGENIC LOADING.

PROPELLANT LOADING OF THE EXTERNAL TANK (ET) SHALL NOT BE INITIATED IF THE 24 HOUR AVERAGE TEMPERATURE FOR THE PRECEEDING 24 HOURS HAS BEEN BELOW 41 DEGREES FAHRENHEIT.

B. FROM START OF ET CRYOGENIC LOADING TO LAUNCH.

THE COUNTDOWN SHALL NOT BE CONTINUED NOR THE SHUTTLE LAUNCHED IF THE AMBIENT TEMPERATURE DURING THIS TIME PERIOD EXCEEDS ANY OF THE FOLLOWING CRITERIA FOR MORE THAN 30 MINUTES.

(1) MAXIMUM TEMPERATURE OF 99 DEGREES FAHRENHEIT

(2) MINIMUM TEMPERATURE OF 37 DEGREES FAHRENHEIT FOR WIND CONDITIONS AT OR ABOVE 5 KNOTS.

(3) MINIMUM TEMPERATURE OF 47 DEGREES FAHRENHEIT FOR STEADY STATE WIND CONDITIONS BELOW 5 KNOTS.

LCC RULE: PRECIPITATION CONSTRAINT

THE SHUTTLE VEHICLE WILL NOT BE LAUNCHED IF:

A. PRECIPITATION EXISTS IN THE FLIGHT PATH

B. ICE ACCUMULATES IN ZERO-ICE OR RESTRICTED THICKNESS AREAS ON THE ET.

Rationale: Thermal Tile Protection

LCC RULE: SURFACE WIND LIMITS FOR LIFT-OFF (MEASURED AT 60' LEVEL)

THE SHUTTLE VEHICLE WILL NOT BE LAUNCHED IF:

WINDS ARE GREATER THAN:

A. 22 KNOTS - STEADY STATE

PRELIMINARY

B. 32 KNOTS - PEAK

Rationale: Design Requirement of JSC 07700 Vol X

LCC RULE: NATURAL AND TRIGGERED LIGHTNING CONSTRAINTS

THE LAUNCH WEATHER OFFICER MUST HAVE CLEAR AND CONVINCING EVIDENCE THAT THE FOLLOWING CONSTRAINTS ARE NOT VIOLATED.

DO NOT LAUNCH IF:

A. ANY TYPE OF LIGHTNING IS DETECTED WITHIN 10 NM OF THE LAUNCH SITE OR PLANNED FLIGHT PATH WITHIN 30 MINUTES PRIOR TO LAUNCH UNLESS THE METEOROLOGICAL CONDITION THAT PRODUCED THE LIGHTNING HAS MOVED MORE THAN 10 NM AWAY FROM THE LAUNCH SITE OR PLANNED FLIGHT PATH.

PLANNED FLIGHT PATH: THE TRAJECTORY OF THE FLIGHT VEHICLE FROM THE LAUNCH PAD THROUGH ITS FLIGHT PROFILE UNTIL IT REACHES THE ALTITUDE OF 100,000 FEET. THE FLIGHT PATH MAY VARY PLUS OR MINUS 0.5 NAUTICAL MILES HORIZONTALLY UP TO AN ALTITUDE OF 25,000 FEET.

DO NOT LAUNCH IF:

B. THE PLANNED FLIGHT PATH WILL CARRY THE VEHICLE

(1) THROUGH CUMULUS CLOUDS WITH TOPS HIGHER THAN THE +5 C LEVEL; OR

(2) THROUGH OR WITHIN 5 NM OF CUMULUS CLOUDS WITH TOPS HIGHER THAN THE -10 LEVEL; OR

(3) THROUGH OR WITHIN 10 NM OF CUMULUS CLOUDS WITH TOPS HIGHER THAN THE -20 C LEVEL; OR

(4) THROUGH OR WITHIN 10 NM OF THE NEAREST EDGE OF ANY CUMULONIMBUS OR THUNDERSTORM CLOUD INCLUDING ITS ASSOCIATED ANVIL

CUMULONIMBUS CLOUD: ANY CONVECTIVE CLOUD WHICH EXCEEDS THE -20 DEGREE CELSIUS TEMPERATURE LEVEL

ANVIL: STRATIFORM OR FIBROUS CLOUD PRODUCED BY THE UPPER LEVEL OUTFLOW FROM THE THUNDERSTORMS OR CONVECTIVE CLOUDS. ANVIL DEBRIS DOES NOT MEET THE DEFINITION IF IT IS OPTICALLY TRANSPARENT

DO NOT LAUNCH IF:

C. FOR RANGES EQUIPPED WITH A SURFACE ELECTRIC FIELD MILL NETWORK, AT ANY TIME DURING THE 15 MINUTES PRIOR TO LAUNCH TIME THE ONE MINUTE AVERAGE ABSOLUTE ELECTRIC FIELD INTENSITY AT THE GROUND EXCEEDS 1 KILOVOLT PER METER (1 KV/M) WITHIN 5 NM OF THE LAUNCH SITE UNLESS:

(A) THERE ARE NO CLOUDS WITHIN 10 NM OF THE LAUNCH SITE: AND,

(B) SMOKE AND/OR GROUND FOG IS CLEARLY CAUSING ABNORMAL READINGS

DO NOT LAUNCH IF:

D. THE PLANNED FLIGHT PATH IS THROUGH A VERTICALLY CONTINUOUS LAYER OF CLOUDS WITH AN OVERALL DEPTH OF 4,500 FEET OR GREATER WHERE ANY PART OF THE CLOUDS ARE LOCATED BETWEEN THE ZERO (0) DEGREE AND THE MINUS 20 (-20) DEGREE CELSIUS TEMPERATURE LEVELS.

E. THE PLANNED FLIGHT PATH IS THROUGH ANY CLOUD TYPES THAT EXTEND TO ALTITUDES AT OR ABOVE THE ZERO DEGREE CELSIUS LEVEL AND THAT ARE ASSOCIATED WITH DISTURBED WEATHER WITHIN 5 NM OF THE FLIGHT PATH

DISTURBED WEATHER: ANY METEOROLOGICAL PHENOMENON THAT IS PRODUCING MODERATE OR GREATER PRECIPITATION

F. DO NOT LAUNCH THROUGH THUNDERSTORM DEBRIS CLOUDS, OR WITHIN 5 NM OF THUNDERSTORM DEBRIS CLOUDS NOT MONITORED BY A FIELD MILL NETWORK OR PRODUCING RADAR RETURNS GREATER THAN OR EQUAL TO 10 DBZ.

DEBRIS CLOUD: IS ANY CLOUD LAYER OTHER THAN A THIN FIBROUS LAYER THAT HAS BECOME DETACHED FROM THE PARENT CUMULONIMBUS WITHIN 3 HOURS BEFORE LAUNCH.

Rationale: Based on the known cloud types and conditions which produce natural and/or triggered lightning

LCC RULE: GOOD SENSE RULE

- EVEN WHEN CONSTRAINTS ARE NOT VIOLATED, IF ANY OTHER HAZARDOUS CONDITIONS EXIST, THE LAUNCH WEATHER OFFICER WILL REPORT THE THREAT TO THE LAUNCH DIRECTOR. THE LAUNCH DIRECTOR MAY HOLD AT ANY TIME BASED ON THE INSTABILITY OF THE WEATHER.

LCC RULE: SRB RECOVERY AREA

DO NOT LAUNCH IF:

A. SEA STATE EXCEEDS SEA STATE CODE 5

B. VISIBILITY LESS THAN 1.5 NM

MANDATORY RECOVERY FOR ASSESSMENT OF SOLID ROCKET REDESIGN

LCC RULE: RANGE SAFETY WEATHER RESTRICTIONS

A. BLAST FOCUS (BASED ON SIMULATION USING WEATHER BALLOON AND WIND DATA)

(1) IF MORE THAN 1 FATALITY PER 100,000 - HOLD OR SCRUB

PRELIMINARY

(2) VALUES BETWEEN 1 PER 100,000 AND 1 PER 1,000,000 REQUIRE EVALUATION BY ESMC COMMANDER

B. CEILING AND VISIBILITY (REQUIRED TO AID RADAR ACQUISITION)

- MUST HAVE CLEAR LINE OF SIGHT UP TO 4500 FEET

C. LIGHTNING (PROTECTION OF RANGE DESTRUCT SYSTEM) SAME AS NATURAL AND TRIGGERED LIGHTNING CONSTRAINTS.

JSC-12820

STS OPERATIONAL FLIGHT RULES

ALL FLIGHTS

FINAL

MAY 9, 1988

PREFACE

THIS PUBLICATION OF THE STS OPERATIONAL FLIGHT RULES, ALL FLIGHTS (JSC-12820) DATED MAY 9, 1988. REPLACES IN ITS ENTIRETY ALL PREVIOUS VERSIONS. THIS DOCUMENT AND THE FLIGHT SPECIFIC STS OPERATIONAL FLIGHT RULES ANNEX (JSC-18308) ARE INTENDED TO BE USED IN CONJUNCTION WITH ONE ANOTHER.

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NASA - JOHNSON SPACE CENTER

FLIGHT RULES

R | RULE 4-64

LANDING SITE WEATHER CRITERIA

THE WEATHER ELEMENT LIMITS CONTAINED IN THIS RULE MUST BE SATISFIED WITH OBSERVATIONS AT THE GO/NO-GO DECISION TIME AND WITH THE FORECAST FOR LANDING TIME (EXCEPT PRELAUNCH EVALUATION OF THE FLIGHT DAY 1 PLS WILL ONLY BE BASED ON THE FORECAST). THE APPROACHES TO BOTH THE PRIME AND BACKUP RUNWAYS AT A GIVEN SITE MUST SATISFY THE CEILING, VISIBILITY, PRECIPITATION, AND THUNDERSTORM PROXIMITY LIMITS LISTED BELOW. WHENEVER AVAILABLE, A WEATHER RECONNAISSANCE FLIGHT WILL PROVIDE A LANDING SITE GO/NO-GO RECOMMENDATION.

A. CEILING AND VISIBILITY LIMITS:

	CEILING (KFT)	VISIBILITY (NOT LESS THAN) (SM)
1. EOM, NEXT PLS RTLS, TAL, AND AOA	10 (8 ①)	7 (5 ②)
2. ELS (ORBIT AND ENTRY PHASES)	10 (8 ①)	5
3. TAL, ACLS, OR ELS (ASCENT PHASE) FOR MAIN ENGINE LIMITS MANAGEMENT (REF. RULE 5-TBD) OR ABORT GAP CLOSURE (REF. RULE 4-26H.3, PERFORMANCE BOUNDARIES)		
a. TACAN AND MLS OPERATING	N/A	N/A
b. TACAN OPERATING, NO MLS	10	5

NOTES:

① APPLIES TO RUNWAY WITH MLS (REF. RULE 3-41, NAVAIDS PRELAUNCH REQUIREMENTS) AND REQUIRES WEATHER RECONNAISSANCE FLIGHT EVALUATION.

② FOR TAL AND AOA WITH MLS: VISIBILITY MAY BE AS LOW AS 5 SM ONLY IF THE FOLLOWING LANDING AIDS ARE VISIBLE AND PREDICTED TO REMAIN VISIBLE ON FINAL APPROACH (WEATHER RECONNAISSANCE FLIGHT EVALUATION):

(a) PAPI's FROM 8K FT TO PREFLARE
(b) BALL BARS FROM PREFLARE TO FINAL APPROACH

THIS RULE IS CONTINUED ON THE NEXT PAGE

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FLIGHT RULES

R	RULE	
	4-64 (Cont)	LANDING SITE WEATHER CRITERIA - Continued A. CEILING AND VISIBILITY LIMITS - Continued *The meteorological limits in this rule must be met with observations at the GO/NO-GO decision time and with the forecast for the landing time. This restriction is necessary to ensure weather violations observed at the decision time (ground or weather reconnaissance) would not permit a GO decision, even if the forecast satisfies the limits. Conversely, if the forecast indicates a violation of the limits at landing time, a NO-GO decision will be made, independent of the current observations. Since the flight day 1 PLS landing time is 5 to 10 hours after launch, the forecast will only be used for the prelaunch flight day 1 PLS evaluation.* *The ceiling, visibility, precipitation, and thunderstorm proximity limits must be met for approaches to both the prime and backup runways, at a given site. This requirement exists because current forecasting capability cannot accurately ensure that a NO-GO condition to one of the backup runways would not result in a NO-GO condition at the prime runway by landing time. Surface wind limits are not required to be met at the backup runways, since the backup runway would only be required if an energy problem occurred dictating a runway redesignation.* *A ceiling is defined as cloud cover >0.5. There are two ceiling limits, one for runways with MLS and a higher limit for runways without MLS. Using MLS, the crew can maintain the approach path accurately to a lower altitude before beginning transition to visual cues (PAPI's, ball-bar, and runway markings). Eight thousand feet is the lowest layer or ceiling permitted using MLS. For runways without MLS, the ceiling minimum is 10K ft. Ceiling limits are established to ensure that the crew has sufficient time after breaking out of the cloud deck to acquire the runway and landing aids during pre-final and landing.* THIS RULE IS CONTINUED ON THE NEXT PAGE

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FLIGHT RULES

R	RULE	
	4-64 (Cont)	LANDING SITE WEATHER CRITERIA - Continued A. CEILING AND VISIBILITY LIMITS - Concluded *The surface visibility limits were established to correspond to the ceiling limits. Slant range visibility down the Orbiter glide slope is not measurable from the ground, nor is slant range a standard meteorological measurement. Therefore, the surface visibility and ceiling limits were established to provide acceptable slant range visibility. Restrictions to surface visibility include smoke, haze, fog, dust, and clouds. The 7 SM surface visibility limit generally applies for all landing conditions, with a couple exceptions. The 7 SM is the horizontal distance component from the runway threshold that correlates to the 10K ft altitude point on the outer glide slope. For AOA (EDW or NOR) or TAL aborts, the visibility requirements can be as low as 5 SM if the runway has an MLS and the weather reconnaissance aircraft verifies that the PAPI's are visible on the approach from 8K ft to preflare and the ball-bar is visible from preflare to final flare. This lower limit is allowed at the TAL or lakebed AOA sites where persistent low altitude/surface dust or smoke may greatly restrict the surface visibility; however, may not pose any significant limitation to crew "slant range" visibility during final approach to landing. This lower surface visibility can not be applied to sites which are prone to visibility limitations due to fog or other transient conditions. The 5 SM limit is the horizontal distance from the runway threshold that corresponds to the 8K ft altitude point on the outer glide slope. Five SM visibility is also the minimum limit used is assessing the usability of an ELS.* *Specific weather criteria are provided for decisions involving abort gap closure or main engine limits management during ascent phase. As documented in Rule 5-TBD and its rationale, in some case following SSME failure, main engine limits will be enabled at the earliest single-engine capability to reach a prime TAL or augmented contingency landing site (ACLS) (utilizing TAL guidance, event though the site itself may not be a program-recognized TAL site). For this purpose, weather criteria may be relaxed, depending on landing aids status at the selected site, as a tradeoff to preclude exposure to SSME limits-inhibited operation for any longer than necessary. In this situation, it is considered less risky to attempt a landing with potentially zero/zero conditions than to continue limits-inhibited SSME operation, provided that both TACAN and MLS are available at the targeted site. If the site has only an operational TACAN, however, the same ceiling and visibility restrictions are applied as for orbit/entry phase ELS GO/NO-GO decisions. In the case of abort gap closure, it is likewise considered reasonable to attempt landing at a site with relatively poor weather conditions as long as the attempt carries a reasonable probability of success, when the alternative is an assured ditching situation.* THIS RULE IS CONTINUED ON THE NEXT PAGE

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FLIGHT RULES

R	RULE	
	4-64 (Cont)	LANDING SITE WEATHER CRITERIA - Continued B. SURFACE WIND LIMITS (DAYLIGHT LANDINGS): 1. THE SURFACE WIND LIMITS FOR ALL LANDING SITES ARE AS FOLLOWS: a. HEADWIND: ≤ 25 KTS b. TAILWIND: ≤ 10 KTS c. CROSSWIND: ≤ 12 KTS NOTE: SURFACE WIND LIMITS REPRESENT PEAK WINDS, INCLUDING MAXIMUM GUSTS (GUSTS MUST BE ≤ 8 KTS ABOVE THE AVERAGE WIND) 2. WITH ONE APU FAILED, SURFACE LIMITS CHANGE AS FOLLOWS: a. CROSSWIND ≤ 10 KTS b. NOT GREATER THAN LIGHT TURBULENCE *This table represents the not to be exceeded limits for wind components for the various landing sites. Headwind limits are established to ensure the Orbiter will land on the runway with touchdown margin. Tailwinds affect the landing by causing longer touchdown ranges, loss of rollout margin, and higher brake energy. Crosswind limits are based upon Orbiter lateral control and tire wear. The limit of 12 KT peak crosswind corresponds to the point where the vehicle handling qualities becomes marginal based on Ames VMS simulations. Gusts of greater than 8 KT above the average/steady state wind corresponds to the 1-sigma (statistical wind profile data; Shuttle Meteorological Group (SMG), Entry FTP 42) deviation for the maximum peak wind allowable (RSS of the peak head/crosswind limits). The limit of ≤ 8 KT was chosen in order to protect for the statistical gust factor (1-sigma) that reaches the headwind/ crosswind limits.* *For one APU failed, the Orbiter is one failure away from having a loss of two APU's at touchdown. With two APU's down, the vehicle will have reduced flight control authority (loss of hydraulic power), braking, and nose wheel steering. In order to protect from this possible loss of control authority, crosswind peak limits are set at 10 KT for all runways. Greater than light turbulence is not allowed for the same control loss reasons.* THIS RULE IS CONTINUED ON THE NEXT PAGE

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FLIGHT RULES

R	RULE	
	4-64 (Cont)	LANDING SITE WEATHER CRITERIA - Continued *Gusts, peak winds above the steady state or average wind, are limited to 8 KT. This 8 KT limit was derived from statistical data which indicated that when a 17 KT average wind is present, the peak wind or gust is ~25 KT (our headwind limit).* *Loss of one APU invokes a crosswind and turbulence restriction. This part of the rule is meant to protect the Orbiter for the loss of a second APU. With two APU's down, the Orbiter will have reduced flight control, braking and nose wheel steering capability. (Refer to paragraph E for an explanation of the turbulence criteria.)* C. SUN ANGLE LIMIT: SUN ON FINAL NOT WITHIN 10 DEG IN AZIMUTH AND 0 TO 20 DEG ELEVATION. *These criteria was established to preclude the Sun from obstructing the crew's vision on final approach.* D. PRECIPITATION AND THUNDERSTORM CRITERIA: 1. PRECIPITATION IS NOT ACCEPTABLE AT THE SURFACE OR ALOFT IN THE PROXIMITY OF THE ORBITER (SEE BELOW). PRECIPITATION INDICATIONS INCLUDE ANY OF THE FOLLOWING: a. VISIBLE RAIN OR VIRGA b. PRECIPITATION ECHO ON WEATHER RADAR c. CLOUD TYPES: CUMULONIMBUS OR CUMULUS CONGESTUS (TOWERING CUMULUS). *The Orbiter is not to encounter precipitation on any approach due to decreased visibility and potential damage to the TPS. Environmental design requirements for the Orbiter were based on the avoidance of in-flight penetration of thunderstorms (ref: appendix 10-10, vol X, Space Shuttle Level II Program Specification). Undesirable aspects of thunderstorms include rain (TPS, structure), hail (TPS, structure, control), severe wind shear (structure), turbulence (control, performance, structure), and natural or triggered lightning (structure, electronic/software systems).* *A 10 n. mi. horizontal proximity distance was chosen based on research experience to minimize risk due to lightning, turbulence, and wind shear and to include forecast uncertainties.* THIS RULE IS CONTINUED ON THE NEXT PAGE

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FLIGHT RULES

R	RULE	
	4-64 (Cont	LANDING SITE WEATHER CRITERIA - Continued 2. THUNDERSTORM PROXIMITY (PRE-DEORBIT AND PRELAUNCH AOA): A SITE WILL BE NO-GO FOR LANDING IF THE THUNDERSTORM (INCLUDING ANVIL), LIGHTNING, OR PRECIPITATION IS WITHIN 30 NM OF THE LANDING SITE. VERTICAL CLEARANCE FROM THESE PHENOMENA, AT THE 30 NM RANGE, MUST BE GREATER THAN 2 NM. ADDITIONALLY, DETACHED OPAQUE THUNDERSTORM ANVILS MUST NOT BE WITHIN 20 NM OF THE LANDING SITE, NOR WITHIN 10 NM OF THE APPROACH PATH OUT TO A RANGE OF 30 NM. *For predeorbit or prelaunch AOA decisions (90 to 125 min forecast), the 30 n. mi. clearance approximates the range to the runway for straight-in approaches at an altitude of 60K ft. Additionally, for these weather phenomena just outside the edge of the 30 n. mi. radius, at least 2 n. mi. vertical clearance must be maintained in order to avoid triggered lightning.* 3. THUNDERSTORM PROXIMITY (PRELAUNCH RTLS AND TAL): A SITE WILL BE NO-GO FOR LANDING IF A THUNDERSTORM (INCLUDING ANVIL), LIGHTNING, OR PRECIPITATION IS WITHIN 20 NM OF THE LANDING SITE OR WITHIN 10 NM OF THE APPROACH PATH TO A RANGE OF 30 NM. VERTICAL CLEARANCE FROM THESE PHENOMENA MUST BE GREATER THAN 2 NM ALONG THE BORDER OF THE HORIZONTAL PROXIMITY BOUNDARY. *For the prelaunch RTLS and TAL decisions (20 to 40 minute forecast), the 20 n. mi. radius clearance approximates a 10 n. mi. distance from each of the approach HAC's. This acceptable proximity distance is reduced from 30 n. mi. radius due to the shorter forecast period. The approach path between 20 n. mi. and 30 n. mi must also be protected by 10 n. mi.* ADDITIONALLY, DETACHED OPAQUE THUNDERSTORM ANVILS MUST NOT BE WITHIN 10 NM OF THE LANDING SITE, NOR WITHIN 5 NM OF THE APPROACH PATH OUT TO A RANGE OF 30 NM. *Detached opaque thunderstorm anvils have the potential for triggered lightning and precipitation should the anvil be penetrated. Therefore, the proximity of the Orbiter from this phenomena is primarily determined by forecast uncertainty. For the 60-to-90 minute forecast, a 10 n. mi. margin will be maintained from the approach path and all of the heading alignment cones (i.e., 20 n. mi. radius from runway). For the 20-to-40 minute forecast decisions, very little margin is protected around the approach path; hence, the 10 n. mi. radius from the runway plus 5 n. mi. clearance along the flight path.* THIS RULE IS CONTINUED ON THE NEXT PAGE

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FLIGHT RULES

R	RULE	
	4-64 (Cont)	LANDING SITE WEATHER CRITERIA - Continued 4. THUNDERSTORM AVOIDANCE AFTER COMMITTED FOR LANDING: A DISTANCE OF 5 NM HORIZONTALLY AND 2 NM ABOVE MUST BE MAINTAINED FROM A CUMULONIMBUS CLOUD, ANVIL, OR ANY OTHER CONVECTIVE CLOUD (RAIN SHOWER) WHOSE TOP EXTENDS TO THE -10° CELSIUS HEIGHT. REAL-TIME THUNDERSTORM AVOIDANCE TECHNIQUES ARE LIMITED TO RUNWAY/HAC REDESIGNATION. NOTE: CLEARANCES WILL BE DETERMINED FROM EITHER RADAR PRECIPITATION ECHOES OR VISUAL OBSERVATIONS. *The post-commitment avoidance clearances (5 n. mi. horizontal, 2 n. mi. vertical) were selected to reduce impact on energy management resulting from runway redesignation and maneuvers and at the same time ensure a reasonably low risk of a natural or triggered lightning strike. Prohibition of penetrating cumulonimbus, cumulus congestus, and opaque anvils is because of concern for triggered lightning and/or rain.* *Reference: Weather Rules Workshop at JSC/MSFC, October, 1987.* *Rule 4-62B, LANDING SITE SELECTION PRIORITIES, references this rule.* E. TURBULENCE: NOT GREATER THAN MODERATE. *Severe turbulence is undesirable due to controllability concerns. Turbulence information comes primarily from area pilot reports. The pilots' reports follow standard definitions for the intensity of the turbulence. The aircraft reaction for the different types of turbulence, as found in the DOD flight information handbook, are defined as follows:* *Light turbulence -- turbulence that momentarily causes slight, erratic changes in altitude and/or attitude.* *Moderate turbulence -- turbulence that causes changes in altitude and/or attitude, but with the aircraft remaining in positive control at all times.* *Severe turbulence -- turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control.* THIS RULE IS CONTINUED ON THE NEXT PAGE

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FLIGHT RULES

R	RULE	
	4-64 (Cont)	LANDING SITE WEATHER CRITERIA - Continued F. ADDITIONAL NIGHT LANDING LIMITS: 1. WHEN AVAILABLE, A WEATHER RECONNAISSANCE AIRCRAFT WILL PROVIDE A GO/NO-GO RECOMMENDATION FOR THE LIGHT ATTENUATION OF THE LANDING AIDS AND THE TOUCHDOWN REGION. 2. CROSSWIND LIMIT IS ≤ 10 KTS PEAK WIND FOR ALL NIGHT LANDING SITES. SURFACE WIND LIMITS INCLUDE MAXIMUM GUSTS (GUSTS MUST BE ≤ 8 KTS ABOVE THE AVERAGE WIND) 3. WIND AND ATMOSPHERIC CONDITIONS MUST NOT REQUIRE USE OF CLOSE-IN AIMPOINT, EXCEPT WHERE CLOSE-IN AIMPOINT PAPI's ARE AVAILABLE. *Because the aimpoint markings and normal geographic visual cues are not visible at night, light attenuation of the landing aids and touchdown region area should be minimal. This evaluation of the light attenuation will primarily depend on the weather reconnaissance aircraft acceptability observations. If, however, an aircraft is unavailable, then visibility will be constrained by ground observations following the daylight visibility limits.* *The crosswind limits are lower for night landings because of the increased crew workload and visibility limitations beyond the runway edges.* *A runway requiring the close-in aimpoint is NO-GO unless there is a PAPI installed. Without the PAPI, the close-in aimpoint is not visible at night (Flt Tech 1, item 3).* 4. FOR LAKEBED LANDINGS WITH ZERO FAULT TOLERANT MLS, MINIMUM CEILING LIMIT IS 20K FT. (REF. RULE 3-41B, NAVAIDS PRELAUNCH REQUIREMENTS, MLS). *For lakebed landings only, single string MLS is acceptable if ceilings are greater than 20K ft. The increased ceiling provides additional time for the crew to compensate for navigation dispersions using visual cues. In addition, the larger area provided by the lakebed environment makes navigation dispersions resulting from the possible failure of the single-string MLS more tolerable.* *Rule 2-1, PRELAUNCH GO/NO-GO REQUIREMENTS, reference this rule.*

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FLIGHT RULES

R	RULE	
	4-64 (Concd)	LANDING SITE WEATHER CRITERIA - Concluded G. WET RUNWAY ACCEPTABILITY CONDITIONS THE FOLLOWING CONDITIONS WILL NO-GO USE OF A SPECIFIC RUNWAY: a. HARD SURFACE 1. STANDING WATER. b. LAKEBED 1. MOISTURE/STANDING WATER. 2. WET/SLUSHY SURFACE MATERIAL. 3. POTHOLES. c. ALL SURFACES 1. STRUCTURAL FAILURES (BREAKTHROUGH) 2. SNOW/ICE. NOTE: CONDITIONS ARE ASSESSED OVER THE ENTIRE PREPARED SURFACE OF RUNWAY *Wet lakebed runways (more than a trace of rain) are not acceptable due to the possibility of hydroplaning and loss of brake effectiveness. Due to the large load bearing requirements of the Orbiter, structural failures are not acceptable on any surface type. Fissures or cracks which may lead to or be evidence of structural failures are not allowable. Wet/slushy material is not acceptable due to the possibility of Orbiter damage from thrown surface material lifted up by the tires. Potholes are not acceptable owing to the possible tire/strut damage caused by impact. For concrete surfaces, standing water may lead to hydroplaning conditions. Snow/ice is not acceptable for any runway surface as loss of traction results. Conditions are assessed over the entire prepared surface of the runway due to the uncertainty of where/when standing water may go. Reference Entry FTP 42. Rules 1-35F and J, LANDING SITES; 2-1F.1 and 3, LANDING SITE WEATHER CRITERIA; 2-31A and D, EXTENSION DAY REQUIREMENTS; 2-81A, EXTENSION DAY GUIDELINES; 3-41A, LANDING SITE WEATHER CRITERIA; 4-2, LANDING SITE CONDITIONS; 4-26, PERFORMANCE BOUNDARIES; 4-62B, LANDING SITE SELECTION PRIORITIES; 4-65, DEORBIT PRIORITY FOR EOM WEATHER; 5-27, LIMIT SHUTDOWN CONTROL; and 8-60, GNC GO/NO-GO CRITERIA, reference this rule.*

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FLIGHT RULES

R	RULE	
	4-65	DEORBIT PRIORITY FOR EOM WEATHER FORECAST VIOLATIONS (REF. RULE 4-64, LANDING SITE WEATHER CRITERIA) AT THE NOMINAL EOM TIME WILL RESULT IN SELECTION OF ONE OF THE FOLLOWING OPTIONS LISTED IN ORDER OF PRIORITY: A. DEORBIT TO PLS AT NOMINAL EOM TIME OR ONE ORBIT LATE TO ALTERNATE RUNWAYS (IF REQUIRED FOR WINDS, SUN ANGLE, OR ISOLATED CLOUD COVERAGE). B. DEORBIT TO PLS EARLY ON EOM DAY. C. DEORBIT TO PLS DAILY OPPORTUNITY. D. DEORBIT TO PLS 24 HRS LATE. E. DEORBIT TO SLS AT NOMINAL EOM TIME. F. RELAX WEATHER CRITERIA. *Deorbit to the primary landing site is always desirable due to convoy/ground operations support and crew familiarity. Options 1 to 4 provide a priority list of options to deorbit to the primary landing site. Should it not be possible to deorbit to the primary site, the secondary landing site will be utilized (option 5). Weather criteria will be relaxed real time should both the primary and secondary landing sites be unacceptable.* *Rule 2-200, CONTINGENCY ACTION SUMMARY, references this rule.*

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