Nowcasting for Space Shuttle Landings at Kennedy Space Center, Florida

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ABSTRACT

Space shuttle launches and landings at Kennedy Space Center (KSC) are subject to strict weather-related launch commit criteria and landing weather flight rules. Complex launch commit criteria and end-of-mission landing weather flight rules demand very accurate forecasts and nowcasts (short-term forecasts of less than 2 h) of cloud, wind, visibility, precipitation, turbulence, and thunderstorms prior to shuttle launches and landings.

The challenges to the National Weather Service Spaceflight Meteorology Group forecasters at Johnson Space Center to nowcast and forecast for space shuttle landings and evaluate the landing weather flight rules are discussed. This paper focuses on the forecasts and nowcasts required for a normal end-of-mission and three scenarios for abort landings of a space shuttle at KSC. Specific weather requirements for a potential emergency landing are the dominant cause of weather-related delays to space shuttle launches. Some examples of meteorological techniques and technologies in support of space shuttle landing operations are reviewed. Research to improve nowcasting convective activity in the Cape Canaveral vicinity is discussed, and the particular forecast problem associated with landing a space shuttle during easterly flow regimes is addressed.

1. Introduction

Many problems can arise that adversely impact launch and landing operations for the space shuttle at Kennedy Space Center (KSC). The most common impacts on these operations include weather, ground support equipment failure, launch vehicle failure, payload failure, or violating other safety criteria. Nearly 75% of all space shuttle countdowns between 1981 and 1994 were delayed or scrubbed, with about one-half of these due to weather (Hazen et al. 1995). In addition, F. Brody et al. (1996, submitted to *Wea. Forecasting*) lists statistics based on Spaceflight Meteorology Group in-house studies of 30 missions between 1991 and 1995. Their most significant finding is that for any given space shuttle mission, there is an 81% probability of forecasters and flight controllers (at Johnson Space Center) being required to assess some type of weather flight rule violation during the final hours of the launch or landing countdown.

Specific weather requirements for a potential emergency landing are the dominant cause of weather related delays to space shuttle launches. This paper focuses on the forecasts and nowcasts required for four scenarios for landing a space shuttle at KSC. These are (a) normal end-of-mission landing and (b) return-to-launch-site landing, abort-once-around landing, and first day primary landing sites (Fig. 1).

Space shuttle landings at KSC's Shuttle Landing Facility (Fig. 2) are subject to strict landing weather flight rules. The landing weather flight rules (Tables 1a–c) and launch commit criteria[1] were estab-

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[1] Space shuttle launches from KSC are also subject to strict weather-related launch commit criteria, but the specifics of the launch commit criteria are beyond the scope of this paper and will not be considered here. However, by extension, the work presented here is also applicable to weather forecasts tailored to the launch commit criteria.

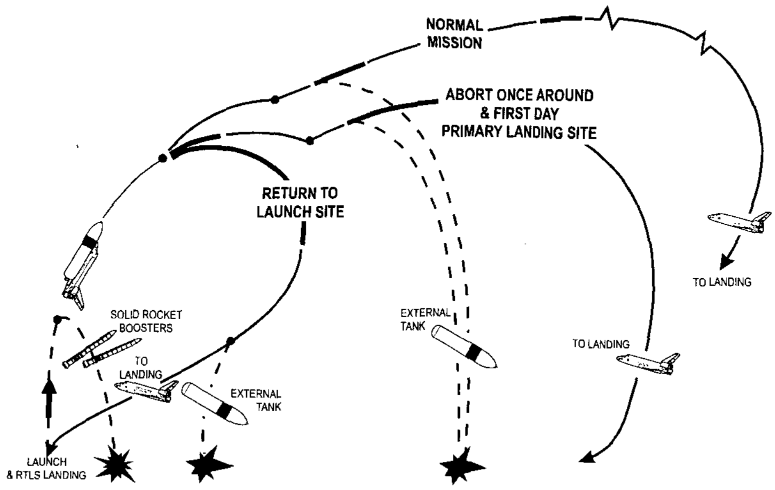

FIG. 1. A depiction of the scenarios considered for landing a space shuttle at KSC. A normal end-of-mission landing, return-to-launch-site landing, abort-once-around landing, and first day primary landing sites.

lished by the National Aeronautics and Space Administration (NASA) (Brody 1993). The National Weather Service Spaceflight Meteorology Group at the Johnson Space Center, Texas, and the U. S. Air Force 45th Weather Squadron at Patrick Air Force Base, Florida, make recommendations regarding landing weather flight rules, which have been assessed and modified by NASA during the 15 years of space shuttle flight from 1981 to the present[2] (F. Brody et al. 1996, submitted to *Wea. Forecasting*).

Two examples of events that have led to reevaluation and changes in weather-related rules in support of the space shuttle program are briefly discussed here. On 28 January 1986, the Space Shuttle *Challenger* exploded shortly after launch on a day in which surface air temperatures were far colder than during any previous shuttle launch. The weather was forecast to be clear and very cold. Ice accumulated in the launch pad area during the night as surface temperatures remained below freezing for about 11 hours (Weems et al. 1987). Although the launch was held while waiting for ice to melt on the pad, it was determined that the exposure to these cold temperatures contributed to the failure of the O-rings that led to the accident (Report of the Presidential Commission of the Space Shuttle *Challenger* Accident 1986). Aerodynamic pressures placed on *Challenger* from wind shears, which were 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. Uccellini et al. (1986) indicated that several significant shear layers existed at the time of the *Challenger* launch. The synoptic situation indicated a juxtaposition of two different airstreams with the interaction of this regime most pronounced over north-central Florida, with descent maximized just to the west of Florida and ascent located just above and east of Cape Canaveral (Uccellini et al. 1986). Uccellini further describes this regime as one in which the confluence of two different flows in the entrance region of a jet streak is conducive to strong vertical wind shears and turbulence. Findings from the House Committee Report on the *Challenger* accident stated: "Weather, by far, is the most significant factor governing operational decisions, orbiter damage, and landing safety. Ultra-conservative rules prevail because of the predictable unpredictability of Cape weather." (National Research Council 1988).

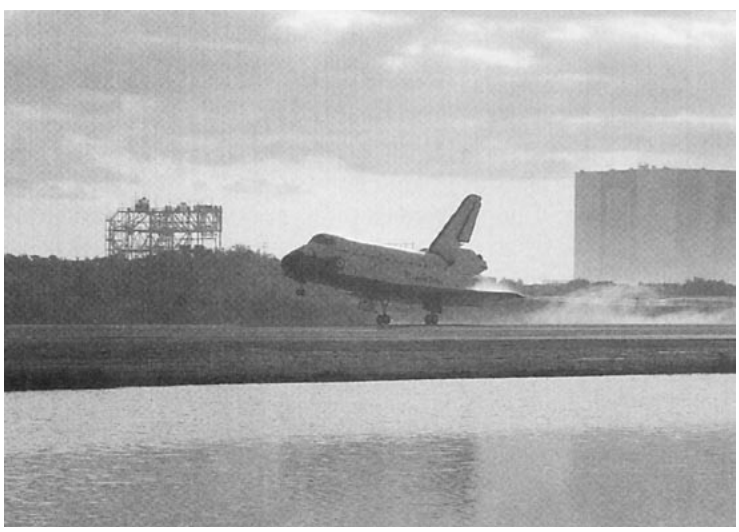

FIG. 2. The space shuttle orbiter *Endeavour* lands at the Shuttle Landing Facility, KSC.

[2] A full discussion of the origin and evolution of the flight rules is beyond the scope of this paper; rather an overview will be given and attention will mainly focus on the nowcast problem. For further reference see Space Shuttle Operational Flight Rules (1995).

TABLE 1a. Weather flight rules for normal end-of-mission landing at KSC. These rules assume redundant Microwave Landing System and no other systems failures on the orbiter. For Tstm, precip, lightning, and detached opaque anvil < 3 h old criteria, the weather limits are defined from the center of the Shuttle Landing Facility runway. Note: Weather flight rules are dynamic and the table below shows the rules as of final submission of this paper. Also, several flight rule changes are currently under review. Details of all flight rules are available from NASA (1995b).

Criteria	Weather limits
Ceiling	≥ 10 000 ft
Obs clds below 10 000 ft at touchdown minus 90 min	≤ 0.2
Visibility	≥ 5 sm
Peak cross wind	≤ 15 kt day, ≤ 12 night
Peak head wind	≤ 25 kt
Avg tail wind	≤ 10 kt
Peak tail wind	≤ 15 kt
Gust (peak-to-average)	≤ 10 kt
Turbulence	≤ Moderate
Tstm, precip, lightning	> 30 nm
Detached opaque anvil < 3 h old	> 20 nm

During convectively active conditions late in the afternoon on 26 March 1987, an unmanned Atlas-Centaur vehicle was destroyed by U. S. Air Force Range Safety because of guidance system failure after the vehicle triggered a four-stroke lightning flash to ground 48 seconds after launch from Cape Canaveral Air Station. The synoptic pattern on this day showed a nearly stationary southwest-to-northeast cold front across the Florida panhandle. Ahead of this front was a squall line also oriented southwest-to-northeast, centered over the Gulf of Mexico and moving east over the Florida panhandle (NOAA 1987). The electrical hazard at Cape Canaveral Air Station was significant throughout the afternoon and extreme at the time of the Atlas-Centaur launch (Christian et al. 1987).

TABLE 1b. Weather flight rules for return-to-launch-site landing at KSC. For Tstm, precip, lightning, and detached opaque anvil < 3 h old criteria, the weather limits are defined from the center of the Shuttle Landing Facility runway. Note: Weather flight rules are dynamic and the table below shows the rules as of final submission of this paper. Also, several flight rule changes are currently under review. Details of all flight rules are available from NASA (1995b).

Criteria	Weather limits
Ceiling	≥ 5000 ft
Visibility	≥ 4 sm
Peak cross wind	≤ 15 kt day & night
Peak head wind	≤ 25 kt
Avg tail wind	≤ 10 kt
Peak tail wind	≤ 15 kt
Gust (peak-to-average)	≤ 10 kt
Turbulence	≤ Moderate
Tstm, precip, lightning	> 20 nm
Detached opaque anvil < 3 h old	> 15 nm

2. Forecasting and nowcasting for space shuttle landings

The National Weather Service Spaceflight Meteorology Group at Johnson Space Center[3] forecasts for abort landing sites and end-of-mission landings based on landing weather flight rules and supports the shuttle flight director at Johnson Space Center, while the U. S. Air Force 45th Weather Squadron at Cape Canaveral Air Station[4] evaluates launch commit criteria for shuttle launches and supports the Shuttle Launch Director at KSC (Brody 1993; Boyd et al.

[3] More information on the Spaceflight Meteorology Group can be obtained from the Universal Resource Locator (URL) for the Spaceflight Meteorology Group Home Page at http://shuttle.nasa.gov/weather/smghome.html.

[4] More information on the 45th Weather Squadron can be obtained from the URL for the 45th Weather Squadron Home Page at http://www.pafb.af.mil/45og/45ws/ws1.htm.

TABLE 1c. Weather flight rules for abort-once-around and first day primary landing sites for landing at KSC. For Tstm, precip, lightning, and detached opaque anvil < 3 h old criteria, the weather limits are defined from the center of the Shuttle Landing Facility runway. Note: Weather flight rules are dynamic and the table below shows the rules as of final submission of this paper. Also, several flight rule changes are currently under review. Details of all flight rules are available from NASA (1995b).

Criteria	Weather limits
Ceiling	≥ 8000 ft
Visibility	≥ 5 sm
Peak cross wind	≤ 15 kt day, ≤ 12 kt night
Peak head wind	≤ 25 kt
Avg tail wind	≤ 10 kt
Peak tail wind	≤ 15 kt
Gust (peak-to-average)	≤ 10 kt
Turbulence	≤ Moderate
Tstm, precip, lightning	> 30 nm
Detached opaque anvil < 3 h old	> 20 nm

1993). The Spaceflight Meteorology Group is an integral part of the Flight Control Team at Johnson Space Center, which is led by the flight director in the Mission Control Center. The Johnson Space Center flight director is responsible for all decisions regarding shuttle landings. Landing weather flight rules and launch commit criteria are independent rules with distinct criteria. Landing weather flight rules must be satisfied with both observed and forecast weather, while launch commit criteria must be satisfied with observed weather only. The Spaceflight Meteorology Group and the 45th Weather Squadron must coordinate extensively to ensure forecast consistency for the weather in the KSC area. For shuttle landings, only landing weather flight rules are considered. The Spaceflight Meteorology Group has the final responsibility for landing weather forecasts and advice to the Flight Control Team at Johnson Space Center.

One goal of the short-term forecast at KSC is to mitigate the impact of weather conditions at the Shuttle Landing Facility on a normal end-of-mission landing and three possible intact aborts (return-to-launch-site, abort-once-around, or first day primary landing sites) (Fig. 1). Additionally, short-term forecast information is used extensively by flight controllers in the Mission Control Center at Johnson Space Center to provide and update landing descent analyses. A fourth intact abort scenario, called transoceanic abort landing, can occur at one of the contingency landing sites in Africa or Spain.[5] Unfavorable weather conditions for return to launch site and transoceanic abort dominate the weather considerations for space shuttle launches (Hazen et al. 1995). Safely landing an orbiter depends in part on the accuracy of the forecast, which must determine whether or not convection will be present, absent, develop over the water and move onshore, dissipate, or intensify. Improvement in the KSC forecast can reduce the weather impact on space shuttle launches. Two examples of weather-impacted shuttle landing attempts at KSC are shown in Bellue and Tongue (1995). The authors discuss the STS-57 and STS-51 missions. STS-57 launched on 21 June 1993 after a weather cancellation on 20 June 1993. The weather on both days was dominated by a southeasterly low-level flow with persistent small showers over the ocean moving northwestward toward KSC. Two attempted STS-57 landings at KSC on 29 and 30 June 1993 were canceled due to weather, and the orbiter finally landed at KSC on 1 July 1993. STS-51 was also affected by weather problems during the launch on 21 September 1993 and the first ever night landing at the SLF on 22 September 1993.

In addition to safety issues, other concerns, such as a 1-orbit delay to a KSC landing, 24-h delay to a KSC landing, or simply unacceptable weather at KSC, may result in a decision to land the orbiter at Edwards Air Force Base, California, instead of at KSC. This is a costly option because a 24-h landing delay costs the space shuttle program about $90,000 at Johnson Space Center, while an Edwards landing costs the space shuttle program about $1 million (Bellue and Tongue 1995; NASA 1995a) and 5–7 days of processing time for its next mission (NASA 1995a).

Both modeling and observational studies have concluded that the patterns and locations of Florida convection are directly related to the synoptic conditions (Byers and Rodebush 1948; Estoque 1962; Frank et al. 1967; Neumann 1971; Pielke 1974; Pielke et al. 1992;

[5] Since this option does not involve a landing at the Cape, it is not considered further in this paper.

Nicholls et al. 1991; Boybeyi and Raman 1992; Lyons et al. 1992). These studies demonstrate the importance of the interaction between the synoptic wind field and the sea-breeze circulation in determining the timing and locations of convective activity across the Florida peninsula. The sea-breeze circulation and the normal patterns of Florida convection assume different characteristics depending on whether the prevailing low-level flow has an easterly, westerly, or alongshore component.

Easterly flow regimes typically generate less vigorous convection along the Atlantic coast than westerly flow regimes (Foote 1991). Convection triggered during easterly flow is characterized by small vertical towers that most often form in the morning and produce brief showers. These showers account for fewer than 5% of the total lightning flashes in this area (Blanchard and Lopez 1985). Nevertheless, convection in easterly flow affects ceilings, visibility, surface wind, and turbulence limits for shuttle landing.

The modeling and observational studies show that eastern Florida generally receives rainfall earlier on days with easterly flow than on days with westerly flow. Afternoon convection at KSC in prevailing westerly flow is more predictable than morning convection. The afternoon convection tends to propagate in a steady fashion from west to east and locations of the east and west coast sea-breeze fronts can normally be detected with Doppler radar and satellite imagery (Wakimoto and Atkins 1994). Easterly flow convection, on the other hand, is not necessarily associated with the sea-breeze front nor an overnight land-breeze front (Reap 1994). The convection occurring within the prevailing deep easterly flow has been difficult to detect with satellite imagery since it is a predawn phenomenon and generally consists of low (warm) cloud tops, which are difficult to distinguish from background surface temperatures. Enhancement curves for IR imagery have been developed by National Environmental Satellite, Data, and Information Service in Camp Springs, Maryland, the National Weather Service Spaceflight Meteorology Group at Johnson Space Center, and the Applied Meteorology Unit[6] at Cape Canaveral Air Station to help locate early morning convective showers. The recent deployment of the improved Geostationary Operational Environmental Satellite (*GOES-8*) has also helped this problem through improved image resolution in the infrared.

Radar is an important tool for monitoring convective development and movement, since even a small shoreward-moving shower or thunderstorm presents a distinct hazard to an orbiter trying to land at the Shuttle Landing Facility. Showers located offshore and moving toward KSC will sometimes weaken and dissipate before landfall, leaving conditions safe for a shuttle landing. The lack of an obvious organizing mechanism, such as a sea or land breeze to trigger convective activity, makes forecasting particularly difficult during easterly flow regimes.

Shuttle reentry into the earth's atmosphere and subsequent landing descriptions are briefly addressed here to provide basic background information related to landing weather forecasts and nowcasts. A full description is beyond the scope of this paper, plus several flight rules have changed during the writing of this paper, and at the time of final submission of this paper several flight rule changes are under review. Details of all flight rules are available from NASA (1995b).

a. End-of-mission landing

All criteria refer to observed and forecast weather conditions except for the 2/10 cloud rule, which is required to be observed only. A final go/no-go decision is made for an end-of-mission landing based on a forecast issued by the Spaceflight Meteorology Group approximately 90 min prior to landing and the observation from the Shuttle Landing Facility "deorbit" decision time. The end-of-mission landing occurs approximately 60 min after the orbiter performs a "deorbit burn" maneuver. The deorbit burn maneuver slows the orbiter and moves it from its on-orbit spacecraft configuration into an aircraft configuration to reenter the earth's atmosphere and glide to a landing (Fig. 3). Once the burn has occurred, the orbiter is constrained to continue on its planned trajectory to a

[6] The Applied Meteorology Unit (AMU) is a tri-agency cooperative effort for transitioning new techniques from the research arena to improve operational weather forecasting and analysis in support of the space shuttle and the National Space Program (Manobianco et al. 1996; Ernst and Merceret 1995). It is operated by ENSCO, Inc. under contract to NASA and is collocated with the 45th Weather Squadron at Range Weather Operations (RWO) on Cape Canaveral Air Station, Florida. The AMU supports RWO forecasters who provide weather support for shuttle and expendable vehicle ground processing and launches, the National Weather Service forecasters at Johnson Space Center (Spaceflight Meteorology Group), who provide weather support for shuttle on-orbit and landing operations, and the National Weather Service Office in Melbourne, Florida, which provides daily regional forecasts.

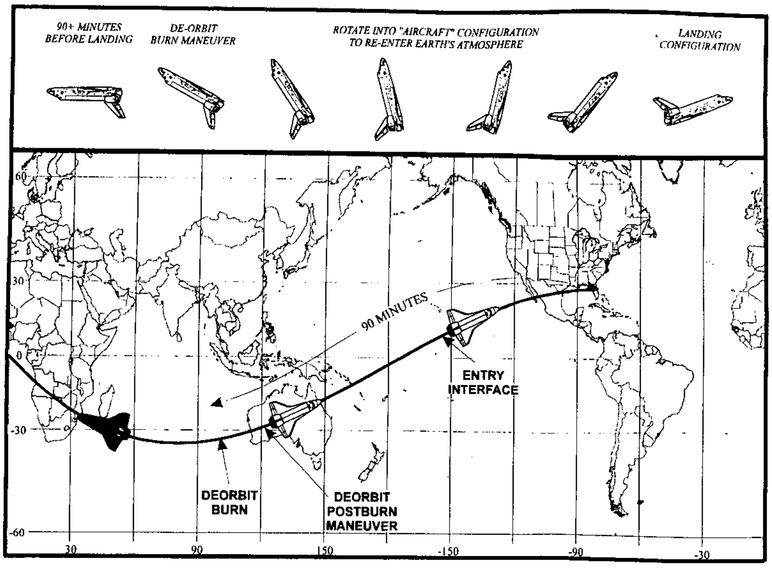

FIG. 3. Depiction of last part of a final ground track by a space shuttle orbiter prior to a landing at KSC.

landing at the planned landing site—there is no turning back. Thus, an accurate forecast is critical for a safe landing.

The weather flight rules for the orbiter during an end-of-mission landing are strict relative to most other aircraft, and observed and forecast conditions for end-of-mission landing time must meet or exceed those shown in Table 1a. If the landing weather is observed or forecast to be worse than these criteria, the landing is postponed, the landing location is changed, or at the discretion of the flight director and Mission Management Team, the flight rule may be "waived."

For a normal end-of-mission, the ceiling must be greater than 10 000 ft. Peak cross winds of less than 12 kt at night and 15 kt during day are the limits placed on a normal landing based on orbiter design as well as other factors. Some phenomena that generate surface wind changes include synoptic-scale fronts, sea-breeze fronts, thunderstorm outflows, diurnal processes, synoptic-scale gradients, and vertical mixing. Generally, the smaller the scale of the phenomenon, the more difficult it is to observe and forecast. This places emphasis on techniques to track and forecast common Florida mesoscale phenomena capable of producing surface winds in excess of orbiter landing limits.

The visibility restriction to greater than 5 statute miles allows the orbiter pilot to see the runway for landing. Morning fog, sometimes caused by a weak land breeze, is a common occurrence at the Shuttle Landing Facility and can quickly advect (< 2 h) over KSC from the west where fog forms above wetlands. The AMU has developed a database for the study of weather situations relating to marginal violations of this landing constraint and has performed an extensive fog study and implemented a Fog Susceptibility Index that can be calculated from observations or model forecasts (ENSCO, Inc. 1995).

The "no precipitation" rule is required for a number of reasons, including pilot visibility, wet runway, damage to the orbiter tiles, and the possibility of natural or triggered lightning. Although all space shuttle orbiters have had extensive upgrades (NASA 1995a) to decrease the stopping distance upon landing (better tires, brakes, nose wheel steering gear, and an added drag chute) the runway must be dry for a safe end-of-mission landing. Also, any precipitation with reflectivity values above 30 dB*z* (F. Brody 1996, personal communication) striking the protective heat-absorbing tiles during flight or while the orbiter is on the ground can damage them. At normal landing speeds, some precipitation can pit the tiles making them unusable for future flights, requiring expensive and time consuming tile repair or replacement work. In general, precipitation, thunderstorms, and lightning must be farther than 30 nautical miles (n mi) away from the Shuttle Landing Facility, and this rule must be satisfied by observed and forecast conditions. The orbiter's flight path must have a 10 n mi horizontal clearance and 2 n mi vertical clearance from lightning or precipitation that may produce lightning or induce electrification to the orbiter. The orbiter must avoid anvil clouds because these clouds tend to be highly charged. The orbiter can trigger lightning from anvil clouds less than 3 h old; consequently, a detached opaque anvil must be farther than 20 n mi from the orbiter's flight path. The most difficult precipitation to forecast occurs from small showers and thunderstorms that can develop well within the 90-min landing forecast period. Thus, forecasters must carefully track the development, dissipation, and movement of clouds, areas of low-level convergence, sea breezes, and changes in moisture and stability.

b. Return-to-launch-site landing, abort-once-around landing, and first day primary landing sites

All criteria refer to observed and forecast weather conditions except for first day primary landing site, which is forecast weather only. Based on the type and time of a failure, the mode of an intact abort is determined by the Mission Control Center at Johnson Space Center. The return-to-launch-site mode is the quickest option and permits the orbiter to land 25 min after launch (Fig. 1). During a return-to-launch-site landing, the orbiter jettisons its solid rocket boosters and the external liquid fuel tank, flies downrange to dissipate propellant, and performs critical maneuvers under power to attain a flight path directly for KSC to land at the Shuttle Landing Facility (National Space Transportation System News Reference Manual 1988). An abort-once-around option allows the orbiter to fly once around the earth and then make a normal entry and landing at the Shuttle Landing Facility, Edwards Air Force Base, or White Sands Space Harbor, New Mexico. The abort-once-around requires ~105 min.

Shuttle Landing Facility weather criteria for return-to-launch-site, abort-once-around (Table 1b), and first day primary landing sites (Table 1c) are generally not as strict as the normal end-of-mission conditions. Should any of these landing weather limits be violated, the launch is postponed (however, abort-once-around weather constraints are mission-dependent and observed or forecast weather violating weather flight rule constraints may not impact a launch decision). It should be noted that the flight director in Mission Control at Johnson Space Center has the option to "waive" a weather flight rule (or any flight rule) to allow a launch or landing to occur.

The return-to-launch-site ceiling rule was relaxed in 1995 (NASA 1995b) and allows for ceilings as low as 5000 ft. The abort-once-around and first day primary landing sites low ceilings are now 8000 ft. The cross wind limit is 15 kt day and night for return-to-launch-site but remains 12 kt at night for abort-once-around and first day primary landing sites. The limits for thunderstorms, precipitation, lightning, and anvil cloud are only reduced for return-to-launch-site, as shown in Table 1c.

It is clear that end-of-mission, return-to-launch-site, abort-once-around, and first day primary landing sites weather flight rules demand accurate short-term forecasts of cloud, wind, visibility, precipitation, and lightning at the Shuttle Landing Facility prior to space shuttle launches and landings. Frequent development and dissipation of convective showers and thunderstorms, and the mesoscale impact of Cape Canaveral's geography, present a considerable short-term forecast challenge (Cooper et al. 1982). A strategy to improve the short-term forecasting capability in the KSC area has been to supplement the observing systems in the Florida region to provide better mesoscale observations (especially in the close vicinity of KSC) and to introduce new mesoscale modeling capabilities to the forecasters.

3. Special observing and modeling systems

Data available for forecasting at KSC include conventional surface observations, upper-air observations, three buoys about 15, 65, and 100 km from KSC, weather radar, and satellite imagery. Doppler weather radar (WSR-88D) is located at the National Weather Service in Melbourne with dedicated lines to the Spaceflight Meteorology Group at the Johnson Space Center and the 45th Weather Squadron at Cape Canaveral Air Station. In addition to the conventional observational systems, forecasters have special in situ and remote sensors in the vicinity of KSC and Cape Canaveral Air Station to provide improved observation of mesoscale circulations and lightning activity. The special sensors (Fig. 4) include the KSC/Cape Canaveral Air Station wind tower mesonet (winds, temperatures, and dewpoints) (Boyd et al. 1995), cloud-to-ground lightning detection system (Maier et al. 1995b), inter- and intracloud lightning detection and ranging system (Maier et al. 1995a), ground-based electric field mill network (Maier et al. 1995b), a

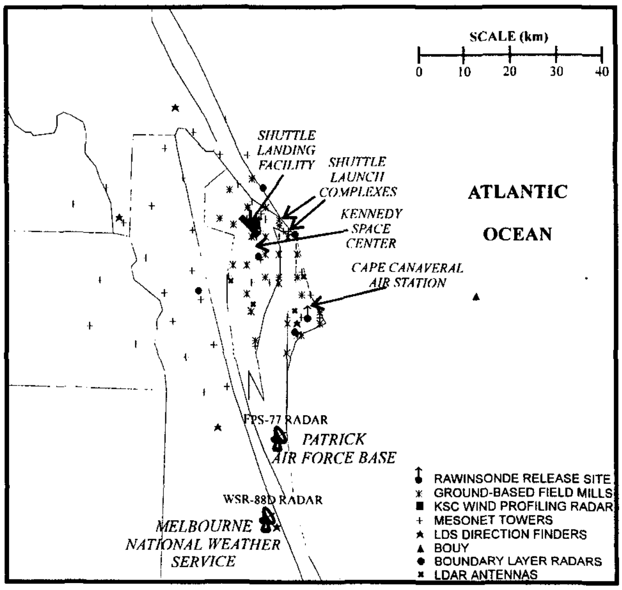

FIG. 4. Map of the Cape Canaveral Air Station and KSC vicinity showing locations of special meteorological sensors.

50-MHz wind profiling radar (Schumann et al. 1995; Wilfong et al. 1993), and 915-MHz boundary layer profiling radars (Heckman et al. 1995).

Also available is a real-time display of the National Lightning Detection Network, direct readout and display of polar orbiter satellite imagery, and rawinsondes and Jimspheres (aluminized mylar constant volume balloons) released at Cape Canaveral Air Station (Bauman et al. 1992). The main meteorological data analysis and display system for the Spaceflight Meteorology Group Johnson Space Center and the 45th Weather Squadron at Cape Canaveral Air Station is the Meteorological Interactive Data Display System (MIDDS) (Rotzoll 1991), which is a McIDAS-based system that integrates other observing and data display systems.

As previously discussed, forecasting for space shuttle operations is a joint effort between the National Weather Service Spaceflight Meteorology Group meteorologists and the 45th Weather Squadron meteorologists. The Spaceflight Meteorology Group meteorologists are responsible for all on-orbit and landing forecasts, while the 45th Weather Squadron meteorologists are responsible for all shuttle launch forecasts. Although U. S. Air Force and National Weather Service meteorologists are geographically separated and have different responsibilities and customers, they coordinate extensively to ensure forecast consistency from prelaunch operations through launch and landing with respect to weather at KSC. Meteorologists at both locations have direct access to KSC and Cape Canaveral Air Station area meteorological data and observing systems via MIDDS, the WSR-88D Doppler radar Principal User Processor, and other common systems.

Even with all the conventional and special observing and data display systems available to the U. S. Air Force and National Weather Service meteorologists, new technology, techniques, and systems are continually being developed to improve the weather support for the space shuttle program. In an effort to improve technology transition and develop forecast techniques for the meteorologists, the Spaceflight Meteorology Group operates a Techniques Development Unit at Johnson Space Center, additionally NASA, the U. S. Air Force, and National Weather Service established the AMU in 1991.

The Techniques Development Unit consists of two National Weather Service meteorologists, assisted by a UNISYS support meteorologist, and a National Oceanic and Atmospheric Administration graduate co-op student. The Techniques Development Unit meteorologists combine the skills of meteorologist and computer scientist. The primary job of the Techniques Development Unit is to customize the Spaceflight Meteorology Group's computer systems for shuttle mission support. During missions, the Techniques Development Unit meteorologists assist the lead forecasters in preparing shuttle landing forecasts, monitor the ingestion of mission critical weather data, troubleshoot computer systems and data flow problems, and create forecast graphics for the Spaceflight Meteorology Groups electronic briefing displays. A "lead Techniques Development Unit meteorologist" is assigned for each mission[7] (Brody 1993).

The AMU is operated by ENSCO, Inc. under contract to NASA and is supervised by one AMU chief (NASA civil service employee) and is staffed by five full-time contractor personnel consisting of meteorologists and computer scientists (Ernst and Merceret 1995). The AMU is responsible for developing, evaluating, and transitioning new technologies, techniques, and systems into operations to support the National Space Program.

Some of the tasks being worked by the AMU include evaluating the two mesoscale models for major forecasting projects. The Regional Atmospheric Modeling System (RAMS) is being used for the Emergency Response Dose Assessment System, and the Parallelized RAMS Weather Simulation System (Lyons et al. 1994), and the Mesoscale Atmospheric Simulation System (MASS) was used to support operational forecasting at KSC (Manobianco et al. 1996). The MASS model is being run on a noninterference basis by the AMU, using a fine mesh grid over the Florida peninsula that has a horizontal resolution of 11 km with 20 vertical levels. The version of MASS being run was developed by MESO, Inc. (Manobianco et al. 1996) and initially delivered to the AMU in March 1993. In April 1995 selected MASS model output was made available to operational meteorologists on a limited basis to evaluate the ability of MASS to predict convective initiation in support of space launch activity.

Other new technologies, techniques, and instrumentation being considered to help improve nowcasts

[7] More information on the Spaceflight Meteorology Group Techniques Development Unit can be obtained from the URL via the Spaceflight Meteorology Group Home Page at http://shuttle.nasa.gov/weather/smghome.html.

and forecasts at KSC and Cape Canaveral Air Station include improvement of the orbiter 90-min landing forecast through development of forecaster and Launch Weather Officer applications for the MIDDS; evaluation of a Microburst Day Potential Index based on equivalent potential temperature profiles to indicate the likelihood of microbursts on a given day; a climatological analysis using data from the KSC 50-MHz Doppler radar wind profiler to evaluate the frequency with which significant wind changes occur within 15 min, 1 h, 2 h, and 4 h; development of training tools to ensure that the Lightning Detection and Ranging display and the concept of operations for its use are well understood; and review and analysis of WSR-88D data for convection initiation and severe/nonsevere storm determination.

Some of the other AMU efforts are described in Ernst and Merceret (1995) and the AMU Quarterly Reports are now available via the internet on the Wide World Web and can be obtained from the URL (http://technology.ksc.nasa.gov/WWWaccess/AMU/home.html) for the AMU Home Page.

4. Discussion and conclusions

To ensure safe landings of the space shuttle, weather-related flight rules demand very accurate forecasts of cloud, wind, visibility, precipitation, turbulence, and thunderstorms at the Shuttle Landing Facility at KSC for space shuttle launch abort landings and for landings at mission end. Rapid small-scale development and dissipation of convection influenced by the mesoscale impact of Cape Canaveral's geography result in a forecast challenge. Subsequent to the reentry burn and during an abort landing, an incoming shuttle is essentially a glider that has one chance to land, leaving little room for error in the forecast of weather conditions for the KSC landing site.

The general pattern of convection over the Florida peninsula is directly related to the synoptic wind field and the interaction of sea-breeze fronts. Meteorologists supporting space shuttle operations have noted that the onset of convective activity during easterly flow is especially difficult to predict since it is frequently not associated with an obvious organizing mechanism such as sea-breeze and land-breeze activity. Seemingly similar synoptic environments are present on days that produce weather ranging from clear skies to heavy showers. The rapid development of clouds and showers on the active days may cause launch and landing weather conditions to change from safe to hazardous within short periods (< 1 h). The potential for rapid changes in the weather has important implications for forecasting in support of space shuttle landings.

A cooperative effort between the authors of this paper, the U. S. Air Force 45th Weather Squadron and the AMU, has been undertaken to improve nowcasts for space shuttle support at KSC during easterly flow. In particular, research cited in this paper was conducted using enhanced datasets collected during the field phase of the Convection and Precipitation/Electrification Experiment (Gray 1991) to better understand this forecast problem.

The MASS model with enhanced horizontal grid resolution was used to capture small convective features present in easterly flow regimes that cannot be resolved by current larger-scale operational numerical models. Assimilation of satellite and weather radar data into the MASS model is being investigated to help overcome the general lack of in situ data over the water east of Florida. Finally, 3D visualization techniques are being examined and applied to analysis and model output to help forecasters view the data more efficiently than conventional methods. Results from these investigations are presented in a companion paper (W. Bauman et al. 1996, submitted to *Wea. Forecasting*).

To make continued progress in short-term forecasting for shuttle activity, ongoing research in the application of new data sources (*GOES-8,* WSR-88D Doppler radar) in operational forecasting is recommended. Integrated moisture data and refractivity profiles from ground- and space-based Global Positioning System (GPS) receivers represent promising new data resources (Businger et al. 1995). Assimilation of *GOES-8,* Doppler radar, and GPS data into mesoscale numerical models of increasing resolution (e.g., Zack et al. 1988; W. Bauman et al. 1996, submitted to *Wea. Forecasting*) may result in tangible improvement in our ability to nowcast convective activity in the vicinity of KSC.

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