Operations of the National Weather Service Spaceflight Meteorology Group

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ABSTRACT

Weather is a significant aspect of most space shuttle launches and landings. The National Weather Service Spaceflight Meteorology Group (SMG) at Johnson Space Center (JSC) in Houston, Texas, provides weather forecasts and advice to support space shuttle operations. SMG has been an integral part of the flight control team in the Mission Control Center at JSC since 1962. Space shuttle weather support is quite complex and specialized, especially compared to more traditional weather forecast operations. SMG forecasts are compared to shuttle weather flight rules to advise the flight director on launch and landing decisions. Perhaps the most critical aspect of SMG's weather support is the ''90-min forecast'' issued prior to landing, supporting the Mission Control Center's ''go'' or ''no-go'' deorbit burn decision. Once the deorbit burn has occurred, the shuttle must land at the designated landing site at the designated time. SMG's forecast must be precise, accurate, and clearly communicated.

Meteorological data acquisition and display is critical for analysis and forecasting, and for briefing the flight control team. Primary systems used are the Meteorological Interactive Data and Display System and the Weather Surveillance Radar-1988 Doppler Principal User Processor.

This article describes SMG functions, operations, data acquisition and display systems, and shuttle launch and landing weather forecast scenarios.

1. Introduction

The National Weather Service (NWS) Spaceflight Meteorology Group (SMG) provides weather forecasts and briefings to support space shuttle operations of the National Aeronautics and Space Administration (NASA). SMG provides forecasts for surface and upper-air parameters for all potential shuttle landing sites, from postlaunch abort contingencies at U.S. and overseas landing sites, to the final end-of-mission (EOM) landing at Kennedy Space Center (KSC) Florida, or Edwards Air Force Base (EDW), California. SMG is an integral part of the Mission Control Center (MCC) flight control team at NASA's Johnson Space Center (JSC) in Houston, Texas.

Weather is a significant aspect of most shuttle launch and landing decisions. An internal study of 30 missions between 1991 and 1995 found that 80% of all launch and landing countdowns (i.e., within 6 h of launch or landing) encountered shuttle landing weather flight rules (NASA/JSC, 1997) violations. These violations were either observed during the countdown, forecast to occur, or were both observed and forecast.

Shuttle weather support operations are extremely complex due to the highly specialized nature of shuttle weather support requirements, relatively restrictive launch and landing time frames and weather constraints, and the extensive coordination and planning required to ensure complete meteorological support. SMG forecasts range from the microscale to hemispheric scale. NASA requires short- to medium-range (1–6 day) forecasts for mission planning and precise short-term (0–12 h) forecasts to ensure safety of the shuttle flight during the critical landing and prelanding phases. The ability to provide this critical support depends on forecasters' skill and experience, the capabilities for ingesting and displaying large volumes of high-resolution weather data, and a capacity to work effectively as part of a decision-oriented flight control team. This article describes SMG operations, technologies, and analysis and forecast techniques used to provide this support.

Section 2 of this paper describes space shuttle weather support. Section 3 describes data acquisition and display. Brief case studies of mission support scenarios are listed in section 4.

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2. Space shuttle weather support

a. Forecast responsibilities

SMG's lead forecasters have final responsibility for shuttle landing weather forecasts and advice to the NASA flight director, flight control team, and mission management team (MMT). This includes EOM landing forecasts as well as launch-day forecasts for return-to-launch-site (RTLS) landings, transoceanic abort landings (TAL), abort-once-around (AOA) landings, and first-day PLS landings (Brody 1993). Lead forecasters rotate through assignments as the ''lead'' and ''assistant lead'' forecaster for each shuttle mission. SMG's technique development unit (TDU) meteorologists are also computer specialists whose primary functions include customizing SMG's MIDDS system for operational weather support, performing computer systems management, and working operational mission support shifts.

While SMG has forecast responsibility for all shuttle landings and potential landings, the U.S. Air Force 45th Weather Squadron (45WS) at Cape Canaveral Air Station (CCAS) provides weather support for shuttle launches from Kennedy Space Center (Boyd et al. 1995). Since launch and RTLS are separated in time by about 25 min and in distance by about 3 mi (i.e., launch pad vs landing runway), extensive coordination occurs between SMG and 45WS prior to each shuttle launch. The division of forecast responsibility is due to 1) the difference between weather *launch commit criteria* (LCC) (NASA/JSC 1997b) for launches and weather *flight rules* (NASA/JSC 1997) for landings, and 2) the inherent advantage of ''dedicated'' on-site support for NASA's launch and landing decision makers. 45WS directly supports the launch director and Launch Control Team at KSC, whereas SMG directly supports the flight director and flight control team at JSC. Command and control of the shuttle switches to the JSC Mission Control Center when the shuttle clears the launch pad. All in-flight and landing decisions are made by the JSC Flight Control Team, led by the flight director.

Training and certification are critical aspects of SMG operations. NASA has strict certification requirements for all shuttle flight controllers. As members of the flight control team, SMG meteorologists must meet certification requirements that consist of a combination of meteorological experience, mission support training, and computer systems proficiency.

Between missions, NASA trains flight controllers almost daily via a variety of ''simulations.'' SMG participates in ascent (launch) and entry (landing) Flight Control Team simulations, supplying weather forecasts and briefings for shuttle landing sites. These flight control simulations promote improved interaction and integration with the flight control team and provide operational training for SMG meteorologists. Additionally, SMG prepares and verifies daily forecasts for shuttle landing sites between missions (Bellue 1993). These forecasts are for projections of 30 min (for the RTLS site and TAL sites), 90 min (EOM sites), 15 h (RTLS, TAL, EOM sites), and 24 h (RTLS, TAL, EOM sites). The experience gained through these daily forecasts is critical for successful shuttle landing weather support.

During and between shuttle missions, SMG provides pilot weather briefings to astronauts for their training flights. SMG provides advisories on the following weather events that will affect the JSC facilities in Houston: lightning within 5 n mi, heavy/excessive rains, high winds (>30 kt), severe thunderstorms, tornadoes, freezing or frozen precipitation, tropical depressions, tropical storms, and hurricanes. Advisories are provided to a variety of weather sensitive operations within Johnson Space Center and to NASA's Ellington Field, about 5 n mi northwest of JSC. When tropical storms or hurricanes threaten the Houston–Galveston area, SMG weather advisory support to JSC continues until the decision is made to close JSC or until the threat has ended. SMG's forecasts and advice to JSC management are critical factors in their decision processes on whether and when to close JSC.

SMG is the staff weather office for Johnson Space Center. SMG meteorologists participate in evaluations of weather-related issues, such as proposed weather flight rules changes, landing site instrumentation upgrades, and landing site climatology. SMG provides documentation of shuttle landing weather forecasts and observations, and participates in postlanding analyses of weather-related shuttle performance. SMG meteorologists conduct formal weather training courses for flight directors, flight controllers, and astronauts. Informal training occurs frequently as NASA personnel visit SMG to obtain forecasts, outlooks, and briefings, and to discuss launch or landing strategies. In addition, SMG collaborates with the NASA Applied Meteorology Unit (Ernst et al. 1995).

b. Types of landings

Space shuttle operations require the option for several types of landing scenarios, which are summarized in Table 1. RTLS would occur if the shuttle experiences a major problem within about the first 3 min of ascent. An RTLS landing requires the shuttle to turn, descend, and land at the Shuttle Landing Facility (SLF) at KSC, 3 n mi west of the launch pad. This landing would occur about 25 min after launch. A TAL would occur if the shuttle experienced a major problem within the first 8 min of flight. In the TAL scenario, the shuttle would descend and land at one of the predesignated shuttle TAL sites: Zaragoza, Spain; Moron, Spain; Ben Guerir, Morocco; or Banjul, The Gambia. A TAL landing would occur approximately 35 min after launch. Two other launch abort landing scenarios include AOA and 1st Day PLS. These landings may be directed by the flight director if a major problem occurs early in the ''on-orbit'' phase of the shuttle flight. An AOA landing would occur

TABLE 1. Space shuttle landing scenarios.

Landing type	Time after launch*	Location(s)	Weather required for shuttle launch/landing
RTLS	25 min	KSC	Obs and fcst go
TAL	35 min	Zaragoza, Spain Moron, Spain Ben Guerir, Morocco Banjul, The Gambia	Obs and fcst go at ≥ one TAL site
AOA	105 min	EDW WSSH KSC	No constraints
1st day PLS**	3–10 h	EDW WSSH KSC	Fcst go for designated PLS landing time
EOM	7–16 days	KSC, EDW, WSSH	Obs and fcst go

* Times may vary, depending on shuttle ascent trajectory and inclination of orbital path.
** Refers to third through sixth Revolution PLS, which is designated prior to each launch.

about 105 min after launch at one of the U.S. landing sites: KSC, EDW, or WSSH. A 1st Day PLS could occur between the third and seventh orbits, or from about 3 through 10 h after launch, depending on the inclination of the flight and available landing opportunities. A 1st Day PLS landing would occur at KSC, EDW, or WSSH. On-orbit PLS selection involves the Flight Control Team predesignating a U.S. landing site (based on runway conditions and the weather forecast) for planning in case the shuttle experienced a problem requiring it to deorbit quickly and land. EOM is the scheduled, planned landing to conclude the shuttle mission. SMG issues forecasts and detailed weather briefings for all shuttle landing scenarios. For EOM landings, KSC is normally the preferred shuttle landing site. Figure 1 displays landing site locations. Figure 2 shows TAL site locations.

c. *Weather flight rules*

Shuttle weather flight rules are designed to ensure safety of flight and take into account the maneuverability constraints of the shuttle, slant range (diagonal) visibility considerations, protection against tile damage, and protection against lightning and triggered lightning. Shuttle weather flight rules are much more restrictive than flight rules for commercial or general aviation. For example, certain commercial aircraft at airports with advanced navigational aids have no ceiling or visibility restrictions, whereas Shuttle end-of-mission landing limits at KSC are ceilings of at least 8000 ft and visibility of at least 5 statute miles. Also, shuttle weather flight rules stipulate no rain or thunderstorms (including anvils) within 20 n mi for RTLS and TAL, or within 30 n mi for EOM. Table 2 shows a set of flight rules for a daylight shuttle EOM landing at Kennedy Space Center. Multiple variations exist in shuttle weather flight rules for different landing sites and landing scenarios (e.g., day vs night, EDW vs KSC, RTLS vs EOM).

In order for the shuttle to launch, weather conditions must be observed *and* forecast "go" (i.e., within limits established by the shuttle weather flight rules) at the RTLS site and at least one TAL site, and must be forecast go at the 1st Day PLS site. Additionally, the weather must be observed go at launch time with respect to shuttle launch commit criteria as monitored by 45WS. For landing, weather conditions must be observed and forecast go at the designated site. During launch and landing counts, SMG forecasts are compared directly to the weather flight rules to assess if conditions are go or no go. The NASA flight director at JSC has the final decision-making authority for evaluating weather flight rules and making launch recommendations or landing decisions based on these rules. In practice, the flight director relies heavily on SMG meteorologists for

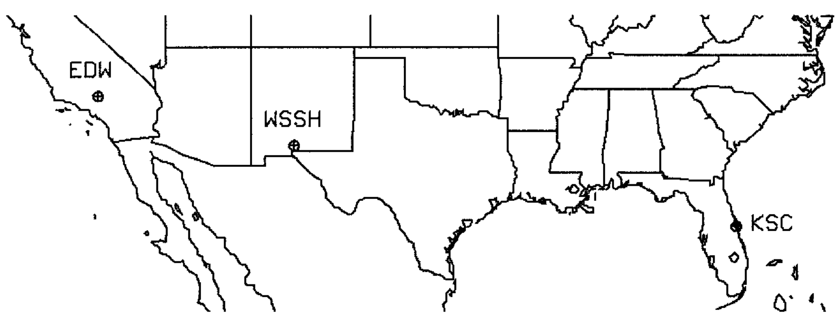


FIG. 1. U.S. shuttle landing sites: KSC = Kennedy Space Center, FL; WSSH = White Sands Space Harbor, NM; EDW = Edwards Air Force Base, CA.

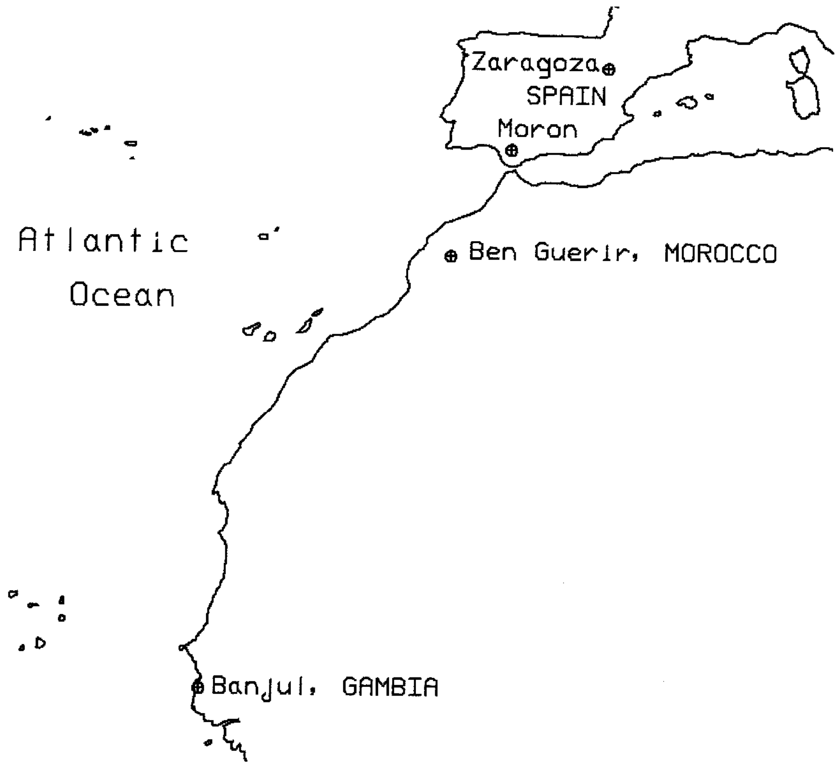


FIG. 2. Transoceanic abort landing (TAL) sites.

weather advice and recommendations with respect to these flight rule–based decisions.

d. SMG forecasts and briefings

SMG's formal weather forecast support to NASA begins 2 days before launch and continues throughout the mission until the shuttle lands. Forecasts describe clouds, visibilities, precipitation, winds, and turbulence. In addition, upper-air wind forecasts are issued for altitudes up to 80 000 ft. Temperature, altimeter setting, and density altitude forecasts are issued within 6 h of launch and landing. Figures 3 and 4 show examples of SMG forecasts. Weather briefings typically include a brief synoptic explanation, the forecast rationale, and, when applicable, alternate weather scenarios. Briefings highlight the timing of anticipated weather events during launch "windows" and, for EOM landings, they describe how the weather might impact decisions for all landing sites and landing opportunities.

TABLE 2. Space shuttle weather flight rules: *daylight* end-of-mission (EOM) landing at Kennedy Space Center.*

Parameter	Limits
Cloud ceiling height	8000 ft
Visibility	5 n mi
Crosswind-peak	15 kt
Headwind-peak	25 kt
Tailwind-peak	15 kt
Tailwind-average	10 kt
Average vs. peak wind	10-kt difference
Precipitation	Not within 30 n mi
Thunderstorms including anvil	Not within 30 n mi
Detached opaque anvil less than 3 h old	Not within 20 n mi
Turbulence	Moderate

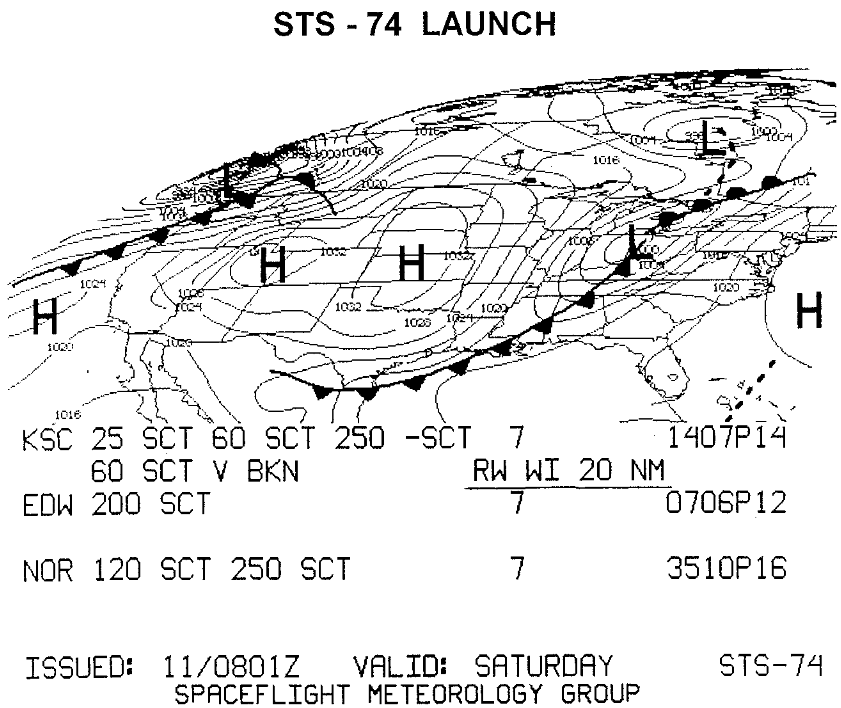
* Flight rules vary depending on landing site, day vs night, type of landing, mission duration, and landing navaids available.

e. Mission support timelines

Planning and coordination for a shuttle mission begins about 5 weeks before the scheduled launch. Documentation and follow-up work may continue for 1–3 months after landing, depending on the complexity of the weather events associated with the mission and the number of operational issues to be resolved. Table 3 lists an abbreviated SMG mission support timeline for a shuttle reentry and landing. The following sections briefly highlight important phases of the prelaunch, on-orbit, and prelanding support timelines.

1) PRELAUNCH SUPPORT

All prelaunch briefings include forecasts for RTLS at the KSC Shuttle Landing Facility (SLF), TAL sites, the AOA sites, and the 1st Day PLS sites. The first formal prelaunch weather briefing is conducted at the "L − 2" day MMT briefing, usually about 48 h prior to



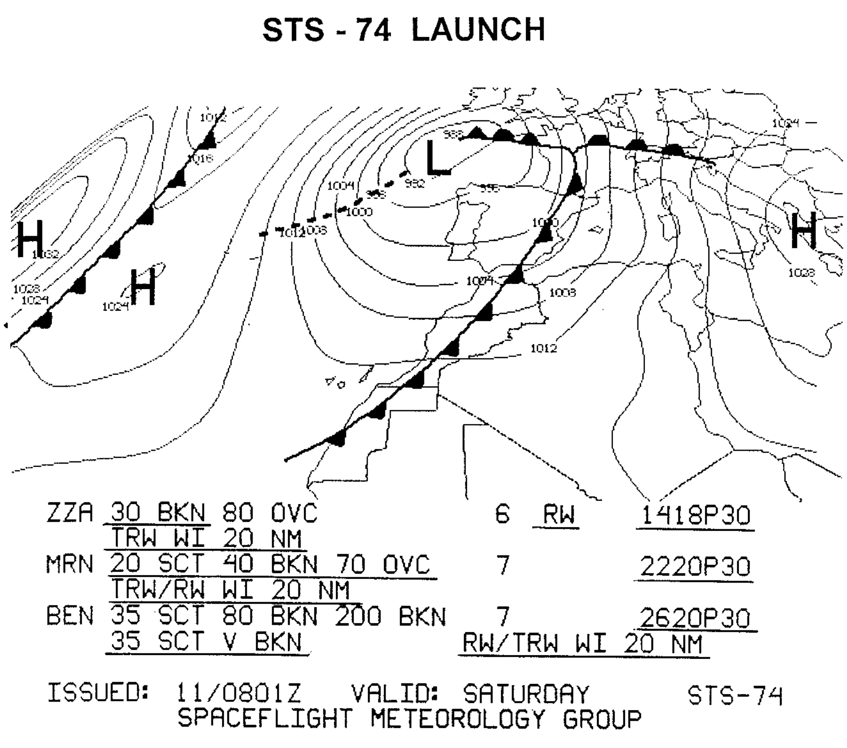


FIG. 3a. SMG 5-h forecast graphic issued at 0800 UTC 11 November 1995 for STS-74 launch attempt. Underlined items denote forecast flight rule violations. Cloud heights are in hundreds of feet, visibility is in statute miles, and wind speed is in knots.
Fig. 3b. Same as Fig. 3a but for TAL sites.

SPACEFLIGHT METEOROLOGY GROUP

UPPER WIND FORECAST

VALID: NOV 11, 1995 AT 1321Z STS-74

	BEN			MRN			ZZA		
ISSUED:	11-11-95	0800Z		11-11-95	0800Z		11-11-95	0800Z	
	HGT (FT)	DIR/ (DEG)	SPD (KTS)	HGT (FT)	DIR/ (DEG)	SPD (KTS)	HGT (FT)	DIR/ (DEG)	SPD (KTS)
	60 K	260/	20	60 K	240/	30	60 K	230/	20
	50 K	240/	50	50 K	230/	35	50 K	230/	35
	38 K	240/	90	38 K	230/	80	38 K	220/	45
	28 K	240/	90	28 K	230/	75	28 K	210/	60
	20 K	240/	70	20 K	220/	70	20 K	210/	55
	12 K	240/	50	12 K	230/	50	12 K	200/	50
	10 K	240/	50	10 K	230/	50	10 K	200/	50
	7 K	240/	45	7 K	230/	45	7 K	200/	40
	5 K	240/	40	5 K	230/	45	5 K	190/	45
	3 K	240/	35	3 K	225/	35	3 K	130/	35
	2 K	240/	30	2 K	225/	35	2 K	130/	35
	1 K	240/	30	1 K	225/	35	1 K	130/	35
	SFC	260/20P30		SFC	220/20P30		SFC	140/18P30	

FIG. 4. SMG 5-h upper-wind forecasts issued at 0800 UTC 11 November 1995 for STS-74 launch attempt: BEN = Ben Guerir, Morocco; MRN = Moron, Spain; ZZA = Zaragoza, Spain.

launch. The next milestone is the "L − 1" day MMT briefing given about 24 h prior to launch. The astronaut crew is also given a separate, detailed briefing about 24 h prior to launch. The "tanking" MMT briefing is given 10 h prior to the scheduled launch time. At this point, the NASA mission management team makes a go or no go decision on whether to fill the external (orange-colored) tank with propellant and proceed with the launch count. Within 6 h of launch, SMG provides near-continuous weather forecasts, briefings, and updates to the flight director and flight control team on all U.S. landing sites and TAL sites. A separate, detailed weather briefing is provided to the astronaut crew 4 h prior to launch. Shuttle launch windows vary between 5 min and 2.5 h, depending on the orbital mechanics and/or payload considerations of the mission. Direct weather support for RTLS ends about 3 min after launch, when a return-to-launch-site abort landing option ends. Direct weather support for TAL sites ends about 8 min after launch, at main-engine cutoff (MECO), when a transoceanic abort landing is no longer an option. After MECO, the shuttle is committed to enter the "on-orbit" phase of its mission. At that point, the only abort landing options remaining are AOA and 1st Day PLS. If any type of launch abort landing were declared by the flight director, SMG would provide continuous weather updates to the flight director and flight control team until the landing occurred.

TABLE 3. SMG entry support timeline.

Time before TD	Event
TD–5 days	EOM forecasts briefed to MMT, flight director
TD–4	EOM forecasts briefed to MMT, flight director
TD–3	EOM forecasts briefed to MMT, flight director
TD–2	EOM forecasts briefed to MMT, flight director
TD–1	EOM forecasts briefed to MMT, flight director
TD–1100 h	Flight director briefing
TD–900	SMG entry team arrives
TD–630	EOM forecasts issued
TD–515	Flight director briefing
TD–500	Request GOES rapid scan
TD–430	Weather recon aircraft takeoff
TD–400	Flight director briefing; go/no-go payload bay door closing decision
TD–330	Weather recon aircraft lands
TD–300	Begin GOES rapid scan
TD–240	Weather recon aircraft takeoff
TD–230	Flight director briefing
TD–130	Flight director briefing; go/no go-deorbit burn decision
TD–100	Deorbit burn
TD–30 min	Flight director briefing
TD–15	Flight dynamics officer briefing
TD–07	Flight dynamics officer briefing; drag chute deploy decision
TD 0	Landing

TD = shuttle touchdown.

2) ON-ORBIT SUPPORT

During the on-orbit phase, SMG provides forecasts for the next 3 days' landing opportunities at the U.S. landing sites (KSC, EDW, WSSH). These forecasts are used by flight controllers to select the daily primary landing site (PLS), which is used for planning in case the shuttle experienced a problem requiring it to deorbit quickly and land. In addition, SMG would provide weather information about emergency landing sites (ELS) around the world if an emergency shuttle landing is required. Occasionally, weather forecasts are provided to support onboard scientific experiment payloads, especially those that require observations of the earth's surface and atmospheric phenomena. Beginning about 5 days before the planned end-of-mission landing, SMG prepares forecasts for the scheduled EOM landing day and for one or two additional contingency days (EOM + 1, EOM + 2). These EOM outlooks are briefed by the mission lead forecaster at the daily MMT meeting. The MMT and flight director typically base their entry (landing) plan on weather forecasts for EOM, EOM + 1, and EOM + 2. Some shuttle missions have been extended or reduced by a full day, with the decision made 2–3 days in advance, based on SMG's forecasts and briefings. As landing day approaches, SMG's EOM forecasts and briefings become more detailed. Informal, unscheduled briefings to MMT members and flight directors may occur several times daily as EOM draws closer.

3) Entry support

Starting about 6 h before the scheduled landing, SMG provides forecasts, briefings, and updates to the flight director and flight control team on a nearly continuous basis. These briefings support mission control center decision points such as the shuttle's payload bay door closing 4 h before landing and the astronaut crew ''suit-up'' at 3 h before landing. SMG's most critical forecast and briefing is made just prior to the deorbit burn decision. This final ''go'' or ''no-go'' forecast is issued directly to the flight director about 90 min prior to the scheduled landing. This time interval is to allow the shuttle to maneuver into deorbit burn position, complete the burn, reenter the atmosphere, and land. *Once the deorbit burn has been initiated, the shuttle must land at the chosen site at the designated time.* The only changes possible are the choice of the final approach path and the choice of runways at the designated landing site. The shuttle is essentially an unpowered glider on descent. After the deorbit burn there is no option to ''go around'' for another landing attempt. This 90-min forecast must be precise, accurate, and clearly communicated in order for NASA flight directors to make well-informed, safe landing decisions. There are usually two or three landing opportunities on a given EOM landing day. A typical scenario provides two landing opportunities at KSC and one at EDW. The two KSC opportunities would be separated by about 90 min (the time it takes the shuttle to orbit the earth once and land). The first EDW landing opportunity would either be on the same revolution as the second KSC opportunity, or could be on the following (third) revolution. If a ''wave-off'' of the first KSC landing opportunity occurs based on observed and/or forecast weather flight rule violations, the flight director may then decide for the shuttle to attempt a landing at the next opportunity at either KSC or EDW, requiring another 90-min go/no-go weather assessment by SMG. If the weather remains unacceptable, the flight director may opt to wave-off the landing until the next day. For most missions, NASA assigns a higher priority to landing at the preferred *site* than to landing on the first EOM day. Thus a forecast of go weather for the *next day* at the *primary landing site* normally takes precedence over go conditions on the *current day* at the *alternate landing site*, given that the option exists to extend the mission and land on the EOM + 1 or EOM + 2 day.

3. Data acquisition and display

SMG provides mesoscale analysis and forecasts for locations scattered around the globe. This creates unique requirements for data acquisition, processing, and display. Two systems perform these functions for SMG: the Meteorological Information and Data Display System (MIDDS) and the WSR-88D Principal User Process (PUP).

a. MIDDS

MIDDS integrates a wide variety of data sources for interactive display by SMG meteorologists. In addition, forecasters use the MIDDS to create briefing graphics and disseminate these products to the Flight Control Team and MMT. The MIDDS is based on the Space Science and Engineering Center's McIDAS system (Suomi et al. 1983; Rotzoll et al. 1991; Young and Fox 1994). McIDAS software provides data acquisition and display capability for surface and upper-air observations, forecasts, and bulletins, as well as numerical model data. In addition, McIDAS provides a programming interface to extend the system's capabilities. The flexibility of the software has allowed the MIDDS to integrate nearly all required data into a single display system. Table 4 summarizes all MIDDS data sources. The following paragraphs will describe the application of some of the MIDDS data sources to spaceflight weather support.

1) Weather satellite

Satellite images provide a critical source of data for landing forecasts. The SMG satellite ingest workstations receive real-time digital *GOES-8*, *GOES-9*, and *Meteosat-6* data. The direct ingest of the GOES satellite data provides SMG access to ''rapid scan'' (roughly 7.5-min interval) or ''super rapid scan'' (down to 1-min interval) infrared and visible satellite imagery from *GOES-8* and *GOES-9*. Hourly *GOES-8* and *GOES-9* sounder data are

TABLE 4. MIDDS data sources.

Data type	Location	Ingest source
Surface observations	Worldwide	IDS, DDS+, and USAF AWN
Upper-air observations	Worldwide	IDS, DDS+, and USAF AWN
Text bulletins	Worldwide	IDS, DDS+, and USAF AWN
GOES-8	Eastern United States/full disk	Direct satellite downlink
GOES-9	Western United States/full disk	Direct satellite downlink
Meteosat-6	Europe/Africa/full disk	Satellite downlink via Wallops Island, VA
NCEP gridded models	Worldwide	Local NCEP ingest and HRS
NCEP profile archive	Selected locations worldwide	Local NCEP ingest
Rawinsonde	Kennedy Space Center	Direct data circuit
Jimsphere (windsonde)	Kennedy Space Center	Direct data circuit
50-MHz Doppler wind profilers	Kennedy Space Center	Direct data circuit
Tower mesonetwork	Kennedy Space Center	Direct data circuit
Cloud-to-ground lightning location	Kennedy Space Center	Direct data circuit
Electric field mill data	Kennedy Space Center	Direct data circuit
Rawinsonde	Edwards Air Force Base	Direct data circuit
Tower mesonetwork	Edwards Air Force Base	Direct data circuit
Rawinsonde	White Sands Space Harbor	Direct data circuit
Tower mesonetwork	White Sands Space Harbor	Direct data circuit
Rawinsonde	TAL sites	Direct data circuit
Automated surface observations	TAL sites	Direct data circuit

USAF = United States Air Force.
AWN = Automated Weather Network.
HRS = High Resolution Data Services.
NCEP = National Centers for Environmental Prediction.

also received and stored, although techniques to apply the sounder data to spaceflight support are still evolving. *Meteosat-6* images covering the TAL sites are received each half-hour.

SMG receives rapid scan imagery starting approximately 3 h prior to each launch and landing. SMG meteorologists track mesoscale features using animation of rapid scan imagery to determine likely areas of cloud formation and dissipation, especially convective clouds. Conventional and mesoscale observations can be superimposed on the satellite images to enhance the mesoscale analyses.

Satellite imagery is also essential for complete evaluation of the weather flight rules. Satellite imagery is used to monitor the development, movement, and dissipation of low clouds, convective storms, and anvil cirrus. Additionally, satellite imagery is used to determine cloud-top temperatures, which are related to potential for electrification. The 3.9- and 11.2-μm GOES channels have been used to improve capabilities to detect, track, and forecast areas of fog and low clouds at night (Ellrod 1995).

2) NUMERICAL MODELS

SMG receives numerical model output including the medium-range forecast model (MRF), aviation model (AVN), Eta Model:Meso-Eta Model, and Nested Grid Model (NGM), and Rapid Update Cycle (RUC). In addition, SMG uses the NGM, AVN, and MRF profile archives (Plummer 1989) to provide vertical profiles of the numerical guidance at shuttle landing sites. The NGM profile archive provides hourly forecast thermodynamic and wind profiles for the landing sites for the first 48 h of the forecast period. The AVN model provides forecast profiles at 6-h intervals for projections out to 3 days, and the MRF provides forecast profiles at 12-h intervals for projections out to 10 days. These profiles are used most by SMG for forecasts projections greater than 6 h. For forecasts projections less than 6 h a mesoscale model is desirable to supplement trend analysis from observational data. SMG has evaluated the Mesoscale Atmospheric Simulation System (MASS) model covering Florida run by the Applied Meteorology Unit (AMU) at KSC. The MASS model was found to be less effective than the RUC in predicting shuttle weather flight rule criteria (Manobianco et al. 1996). A major deficiency in the MASS appeared to be the lack of concentrated data needed for initialization. Developing a mesonetwork observing system across Florida and including other datasets like WSR-88D and profilers into initialization of a mesoscale model will be necessary before mesoscale modeling outperforms current NCEP models in Florida. SMG is participating in an AMU project to assess the utility of the 29-km meso-Eta Model for spaceflight weather support.

3) UPPER-AIR MEASUREMENTS

A combination of direct and remote sensing equipment is used to make upper-air measurements for space shuttle support. Upper-air sounding data are taken at frequent intervals in the hours just before launch and landing at all potential U.S. and TAL landing sites. The 50-MHz Doppler wind profiler at KSC provides a sample of the upper-air winds every 5 min at altitudes from about 6000 to 60 000 ft. A network of five 915-MHz Doppler wind profilers with Radio Acoustic Sounding Systems was recently installed in the KSC area (Heckman et al. 1995). The 915-MHz profiler network will provide detailed wind and virtual temperature measurements from about 500 to 10 000 ft. Weather reconnaissance performed by astronauts flying aircraft at the landing sites provides valuable information concerning clouds, winds, turbulence, visibility, and precipitation. This information is a critical supplement to radar and satellite data for tracking weather changes within about 4 h of launch and landing.

In addition to evaluating the state of the atmosphere, the upper-air measurements are a key to predicting the atmosphere's effects on the shuttle trajectory during landing. SMG forecasters use the observed winds and model profile archives to create the upper wind and turbulence forecasts for each of the U.S. and TAL landing sites (Bellue et al. 1996). The ascent and descent analysis teams at JSC incorporate the observed winds and SMG forecasts into shuttle ascent load models and descent trajectory models. That output is then used by the flight control team to ensure the safe flight of the vehicle during ascent and during planned or emergency landings.

4) Lightning location and atmospheric electric field

The lightning strike to the *Apollo 12* spacecraft in 1969 spurred interest in lightning research at KSC. KSC is now one of the best-instrumented locations in the world for monitoring the atmospheric electric field and lightning (Maier et al. 1995). A network of magnetic direction finders detects and locates cloud-to-ground lightning in the vicinity of KSC (Krider et al. 1976). Forecasters use the cloud-to-ground lightning data in conjunction with WSR-88D data to determine if thunderstorms are occurring within 30 n mi of the SLF and to help determine when anvil cirrus clouds become detached from the parent cumulonimbus cloud. Although no weather flight rules pertain to the electric field values, the MIDDS can access the Launch Pad Lightning Warning System (LPLWS) data to monitor the atmosphere's electric field. The LPLWS can be a valuable system for detecting the electrification of clouds near the SLF.

5) Mesonet data

In addition to the conventional data sources, NASA supports extensive mesoscale surface networks at KSC, WSSH, and EDW. As an example, over 40 meteorological-instrumented towers are included in the KSC network with each tower reporting temperature, dewpoint, and both average and peak wind measurements at several levels between 10 and 54 ft above ground level. In addition, some mesonet towers provide measurements up to 492 ft at KSC and 120 ft at EDW. These mesonet towers are vital for analyzing and tracking wind shift lines like the sea breeze at KSC. This is important for forecasting convective initiation/dissipation as well as crosswinds, headwinds, and tailwinds. Temperature and relative humidity data from the towers also aid in forecasting the development and dissipation of fog or low stratus clouds, which can be critical forecast parameters for shuttle landings at KSC.

b. WSR-88D

SMG's WSR-88D PUP associated to NWSO Melbourne, Florida (KMLB), was one of the first NWS PUPs delivered, in 1992. The greater sensitivity and capability of the WSR-88D radar allows improved detection of most weather features compared with pre-WSR-88D radars (Crum and Alberty 1993). This increased capability has improved SMG's ability to monitor and forecast weather for shuttle support. SMG has used the WSR-88D data operationally to support over 36 space shuttle missions.

Another source of radar data for the KSC area is from the Patrick AFB, Florida, WSR-74C radar, which is enhanced by a McGill processor (Austin et al. 1986). This enhanced radar data is transferred from the Cape Canaveral MIDDS to the JSC/SMG MIDDS, where it may be readily displayed on MIDDS.

The uniqueness of the shuttle weather flight rules causes SMG to utilize the WSR-88D data differently than most other weather offices. For example, the WSR-88D 0.5° base reflectivity product occasionally detects cloud drops and cloud streets. This assists SMG in monitoring and forecasting cloud cover amount and low cloud ceiling development in the KSC area. Lowest-level base reflectivity and velocity products are valuable for locating sea-breeze boundaries, convective outflow boundaries, and other fine lines, which help with tracking wind shifts and forecasting convective initiation and dissipation. Higher-level base reflectivity products and layer composite reflectivity products are used to track movement and location of thunderstorm anvils, which have specific avoidance limits in shuttle weather flight rules. Echo thunderstorm anvils top products are used to monitor convective cell development. Finally, 0.5° base reflectivity and velocity products are both used in detecting and confirming chaff and tracking its movement.

Chaff affecting central Florida was first documented by SMG with the use of the WSR-88D in 1993 (Hermes 1993). Since chaff can "mask" reflectivity returns of precipitation and cloud streets, it has been recognized as a potential problem for analysis and forecasting of shuttle launch and landing weather parameters. Coordination procedures were placed into effect in 1994 by the Department of Defense to stop chaff drops prior to shuttle launches and landings (Roeder 1995).

Another unique aspect of SMG WSR-88D utility is the use of "switch" software on the PUP to accomplish

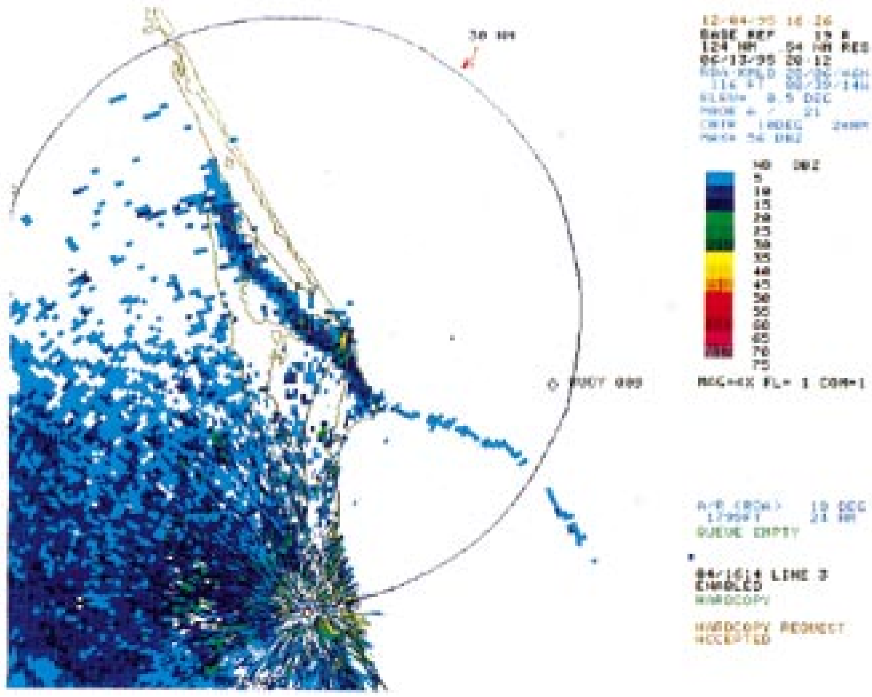


FIG. 5. Melbourne, FL, WSR-88D 0.5° base reflectivity, 2012 UTC 13 June 1995.

SMG's requirement for dual PUP association to two different sites. This software was developed by the WSR-88D Operational Support Facility (OSF) and was installed in 1994. Association to KMLB is required to support space shuttle landing weather forecasts, while association to NWSO Houston–Galveston, Texas (KHGX), is required for issuance of local JSC weather advisories.

SMG has set up a special set of user functions that allows acquisition of data from two WSR-88D sites at the same time. This is accomplished by continually dialing out to one site while being associated to the other site, allowing data from both KMLB and KHGX to be displayed and manipulated at the same time on SMG's PUP. This feature has been valuable during space shuttle missions for monitoring KMLB and Edwards AFB (KEYX) WSR-88D data when landing weather forecasts are required for both sites.

Figure 5 shows a KMLB 0.5° base reflectivity product taken during SMG's support of a shuttle deorbit simulation on 13 June 1995. This figure illustrates the WSR-88D's utility in diagnosing low-1evel boundaries. An unusual boundary is depicted in the 5–15 dBZ reflectivites. This boundary extends from north of the KSC area southward along the coast to near Cape Canaveral, then southeast into the Atlantic. The sea breeze is responsible for this boundary from Cape Canaveral northward, while the boundary southeast of the cape is of unknown origin. The ease of identifying these boundaries and tracking their movement with the PUP is a valuable diagnostic and forecasting capability.

4. Examples of launch and landing forecast scenarios

Virtually each shuttle mission presents a different set of meteorological challenges for shuttle weather forecasters. Below are descriptions of mission forecast scenarios that illustrate the variety and scope of weather forecast issues and challenges. For more in-depth meteorological descriptions, please refer to Hafele and Haller (1991) for TAL weather support, and Bellue and Tongue (1995) and Bellue and Garner (1995) for U.S. landing site weather support descriptions section 4a describes launch scenarios and section 4b describes landing scenarios where weather forecasts were a critical factor in mission success.

a. Launch day impacts of landing weather

1) STS-74 LAUNCH ATTEMPTS: 11 AND 12 NOVEMBER 1995 (TAL WEATHER)

For the STS-74 (*Atlantis*) launch attempt of 11 November 1995, U.S. landing site weather (Fig. 1) for RTLS, AOA, and 1st Day PLS weather was observed and forecast go. The TAL weather observations and forecasts were no go for all three usable northern sites (Fig. 2). Within launch minus 6 h, weather flight rule violations for tailwind, cloud ceilings, and rain showers were observed and forecast for Zaragoza, Spain. At Moron, Spain, and Ben Guerir, Morocco, cloud ceiling and crosswind violations were observed and forecast. Since the STA-74 mission was scheduled to rendezvous with

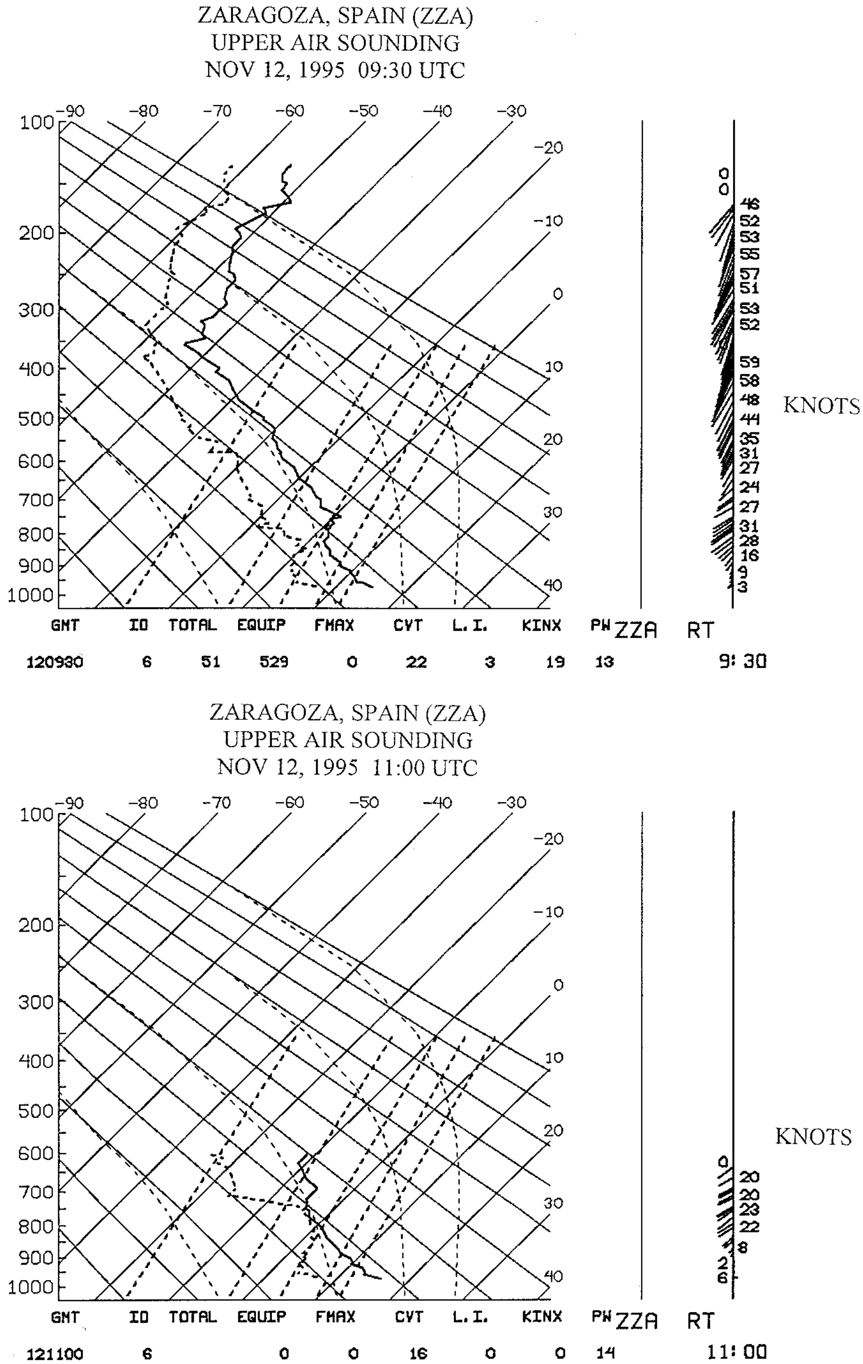


FIG. 6. Zaragoza, Spain, rawinsonde, (a) 0930 UTC 12 November 1995, and (b) 1100 UTC 12 November 1995.

the Russian *Mir* space station, the launch opportunity window was only 7 min long. No-go TAL observations and forecasts continued through the launch countdown. The launch was "scrubbed" (i.e., postponed) for 24 h due to lack of an acceptable TAL site. This marked only the second time in the history of the space shuttle program that a launch was scrubbed based only on no-go TAL weather.

On the next day, 12 November 1995, weather at Moron, Spain, and Zaragoza, Spain, improved to go within 1 h of the scheduled 1230 UTC launch time. Meteosat satellite imagery, frequent rawinsonde releases, and weather reconnaissance aircraft reports played an important part in assessing TAL site weather on this day. Weather concerns for Zaragoza were cloud ceilings, precipitation, and tail wind exceedance. Rawinsonde re-

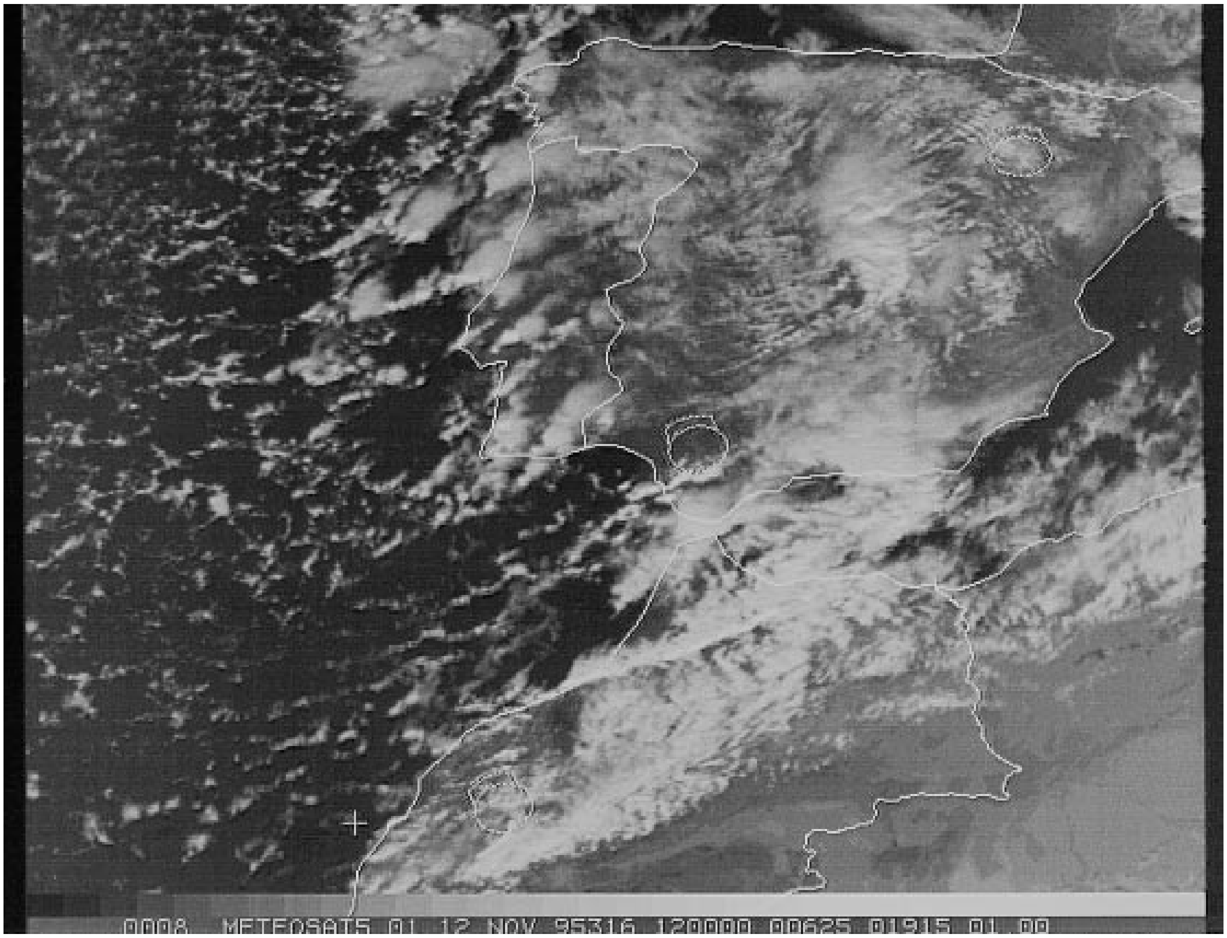


FIG. 7. Meteosat 1-km visible image, 1200 UTC 12 November 1995.

leases leading up to the launch time (Figs. 6a and 6b) showed that winds aloft, which could mix down to the surface, were decreasing in speed as the launch time drew near. Surface observations and satellite imagery animation showed increasing clouds in the hours leading up to launch. However, weather aircraft reconnaissance reports at Zaragoza noted no obstructions to pilot visibility on approach and no rain or virga within 20 n mi of the landing site. Astronaut-piloted weather reconnaissance aircraft observations may take priority over those by ground-based observers since the aircraft is following the shuttle flight path and makes a direct measurement of slant-range visibility. Zaragoza weather became go just prior to launch.

Satellite imagery animation and weather reconnaissance aircraft reports were the basis for amending the Moron forecast to go. Bands of showers and thunderstorms were moving ashore in southwestern Spain. Meteosat imagery animation was crucial for forecasting the formation, curvilinear motion, rapid speed, and dissipation of these showers. However, satellite navigation and parallax errors potentially could have made the Moron weather no go since dissipating rain showers were very close to the edge of the 20 n mi weather flight rule limit for precipitation. Figure 7 shows the 1200 UTC Meteosat satellite image. Weather reconnaissance aircraft reported that the observed location of the showers was just beyond the 20 n mi weather flight rule limit. With two go TAL sites, *Atlantis* was given the go for launch.

2) STS-36 LAUNCH: 28 FEBRUARY 1990 (RADAR, WEATHER RECON AIRCRAFT)

Attempting to launch around midnight local time, the STS-36 (*Atlantis*) launch on 28 February 1990 was delayed because of forecast ceiling and rain flight rule violations for RTLS at KSC and ceiling violations at the TAL sites. The launch count was held at T minus 5 (T − 5) min for launch pad weather (launch commit criteria weather violations), RTLS weather, and TAL weather. Through the launch count, cloud ceilings at KSC remained between 3000 and 5000 ft in rain showers and ranged from 5500 to 7500 ft outside the areas of precipitation. A late report from the weather reconnaissance aircraft indicated that the runway landing aids

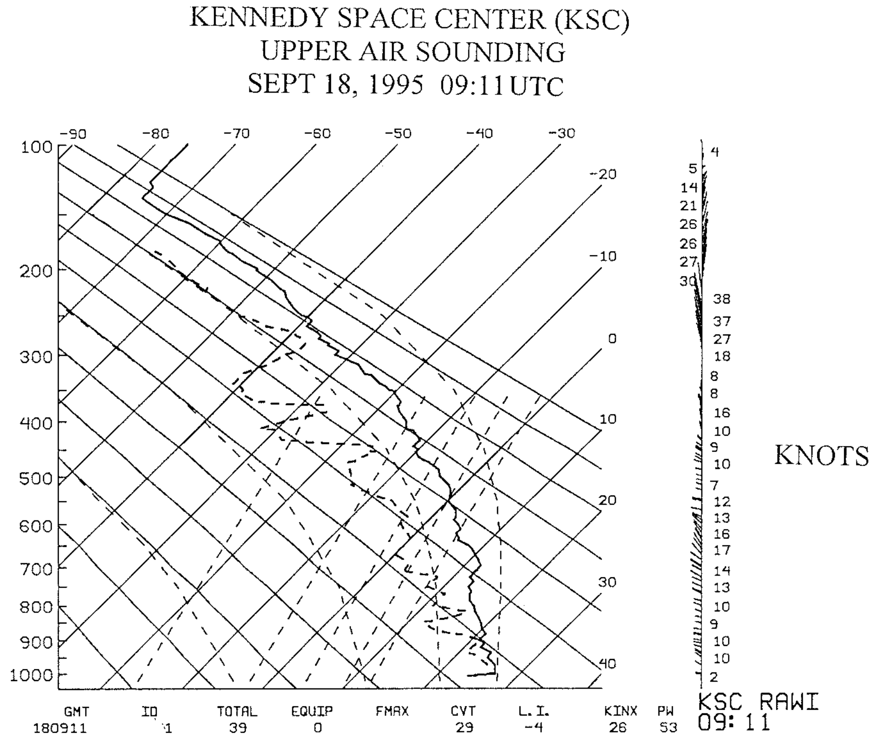


FIG. 8. Kennedy Space Center rawinsonde, 0911 UTC 18 September 1995.

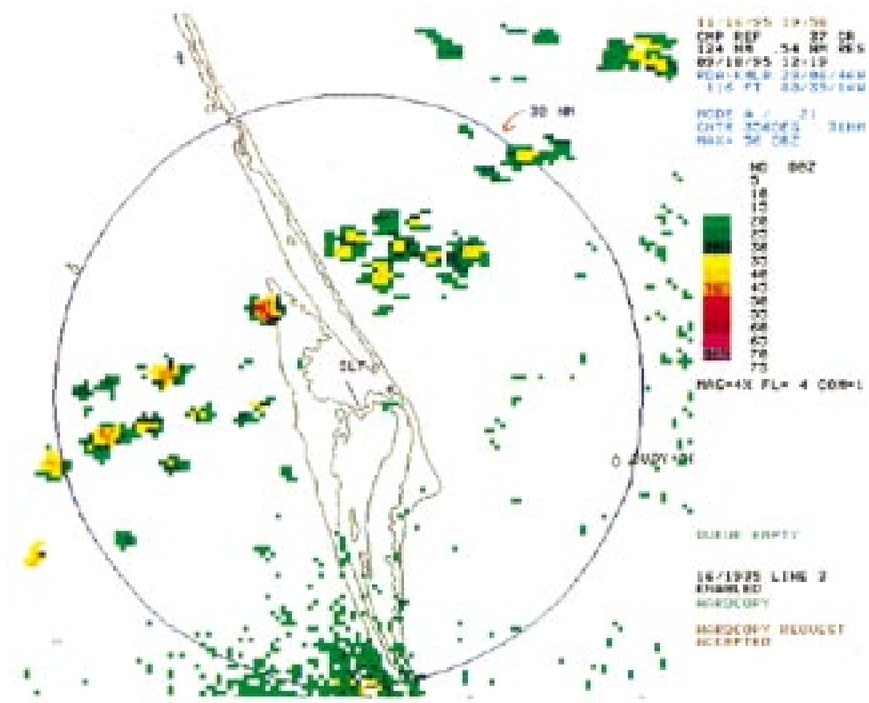


FIG. 9. Melbourne, FL, WSR-88D composite reflectivity, 1219 UTC 18 September 1995.

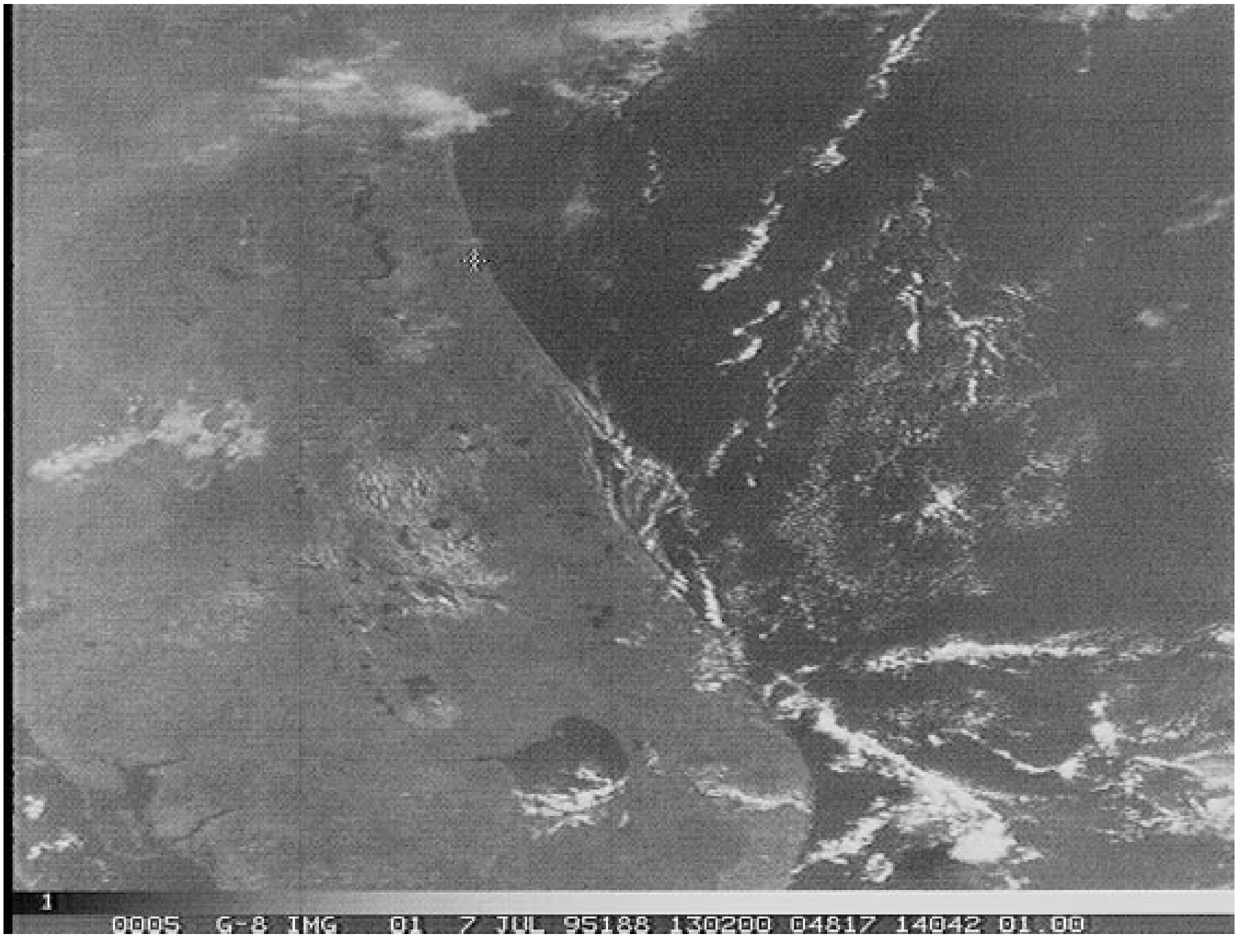


FIG. 10. *GOES-8* 1-km visible image, 1302 UTC 7 July 1995.

were visible at 8000 ft due to the cloud translucence even while the aircraft was in the bases of the cloud layer. Infrared satellite imagery depicted a broad overcast cloud deck across central Florida. Banded rainshowers were moving through the area. Based on WSR-74C radar data from Patrick Air Force Base, SMG predicted that one band of rain showers would move out of the 20-n mi flight rule limit area before another band moved into the 20-n mi area. Forecast timing of the movement of the rainshower bands and reports from the weather reconnaissance aircraft at KSC, as well as improving TAL weather conditions, gave forecasters confidence to update forecasts to go for RTLS and TAL. STS-36 launched successfully with 5 min remaining in the 2.5-h launch window.

b. Landing day impacts

1) STS-69 LANDING WEATHER: 18 SEPTEMBER 1995 (CLOUDS, SHOWERS, FOG)

For the STS-69 (*Endeavor*) landing, a weak surface trough was located just north of KSC. The primary forecast concerns for the KSC morning landing opportunities were visibilities reduced by fog for the first landing opportunity near sunrise (1138 UTC) and low clouds or rain shower development for the second opportunity (1314 UTC). Weather flight rules in effect at that time for EOM landings at KSC stipulated cloud ceilings above 10 000 ft, visibility of 5 n mi or greater, and no rainshowers or thunderstorms within 30 n mi. Figure 8 shows the 0911 UTC 18 September 1995 KSC sounding. The low-level inversion along with light west to northwest low-level winds and high moisture content indicated possible fog development. Additionally, this high moisture content and an unstable air mass indicated the potential for rainshower and thunderstorm development. As deorbit burn decision time approached, weather reconnaissance aircraft reports and local surface observations indicated little fog development around KSC. SMG determined that the convective temperature was unlikely to be reached until after the first scheduled landing opportunity. SMG updated the forecast at the deorbit burn decision point to reflect go conditions for the first landing opportunity. However, the forecast remained no go for the second landing opportunity due to expected development of low cloud ceilings and rain-

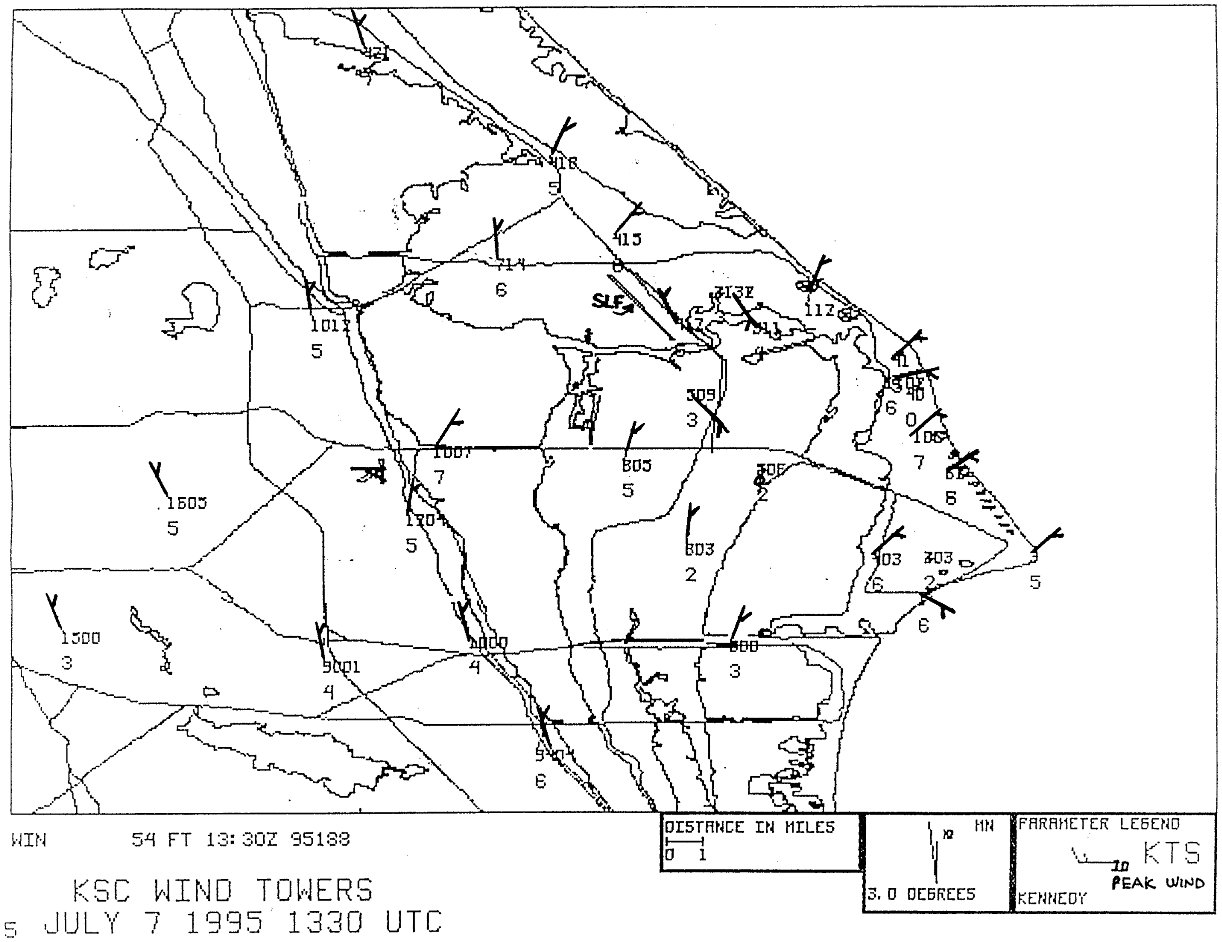


FIG. 11. Kennedy Space Center mesonet 54-ft wind tower data, 1330 UTC 7 July 1995.

showers. Based on SMG's updated forecast, the flight director gave a go for the deorbit burn for the first landing opportunity and the shuttle landed safely at KSC at 1138 UTC. Rainshowers developed within 30 n mi of KSC just 20 min after landing, and weather remained no go through what would have been the second KSC landing opportunity. Figure 9 shows a WSR-88D composite reflectivity product valid 40 min after landing, showing the development of the showers along the surface trough near KSC. In this case, the weather reconnaissance reports, timely upper-air soundings, and the forecaster's experience with local convective climatology were critical in SMG's ability to confidently forecast go conditions for the first landing opportunity and no-go conditions for the second opportunity.

2) STS-71 LANDING (LOW CLOUDS, SEA BREEZE)

The STS-71 (*Atlantis*) landing day, 7 July 1995, began with clear skies. The SMG landing forecast for 1455 UTC called for scattered low clouds at KSC. Shuttle weather flight rules in effect at that time for KSC EOM landings required forecast cloud layers below 10 000 ft to be scattered (5/10 coverage or less). Additionally, for KSC only, weather flight rules in effect at the time stipulated 2/10 or less observed cloud coverage below 10 000 ft at the deorbit burn decision time 90 min before landing. The midmorning sea breeze was expected to develop and push the clouds west of the KSC SLF. The 1055 UTC KSC sounding showed an increase in low-level moisture but drier air above 3000 ft. This indicated an increased potential for low cloud development and coverage but also implied limited vertical development. Low clouds with 3/10 sky coverage developed at the SLF around 1300 UTC (Fig. 10). The sea breeze also developed as depicted in the KSC wind tower mesonet (Fig. 11) but was weak and slow to move inland. Thus, the low clouds were not being pushed west of the SLF as fast as expected. At the 1330 UTC deorbit burn decision point, based on weather reconnaissance aircraft reports, surface observations, local mesonet tracking of the sea breeze, and experience with KSC sea-breeze and cloud development patterns, SMG advised the flight director that the clouds would indeed remain only scattered at the SLF, even though 3/10 low cloud coverage was observed. Based on the confidence expressed in

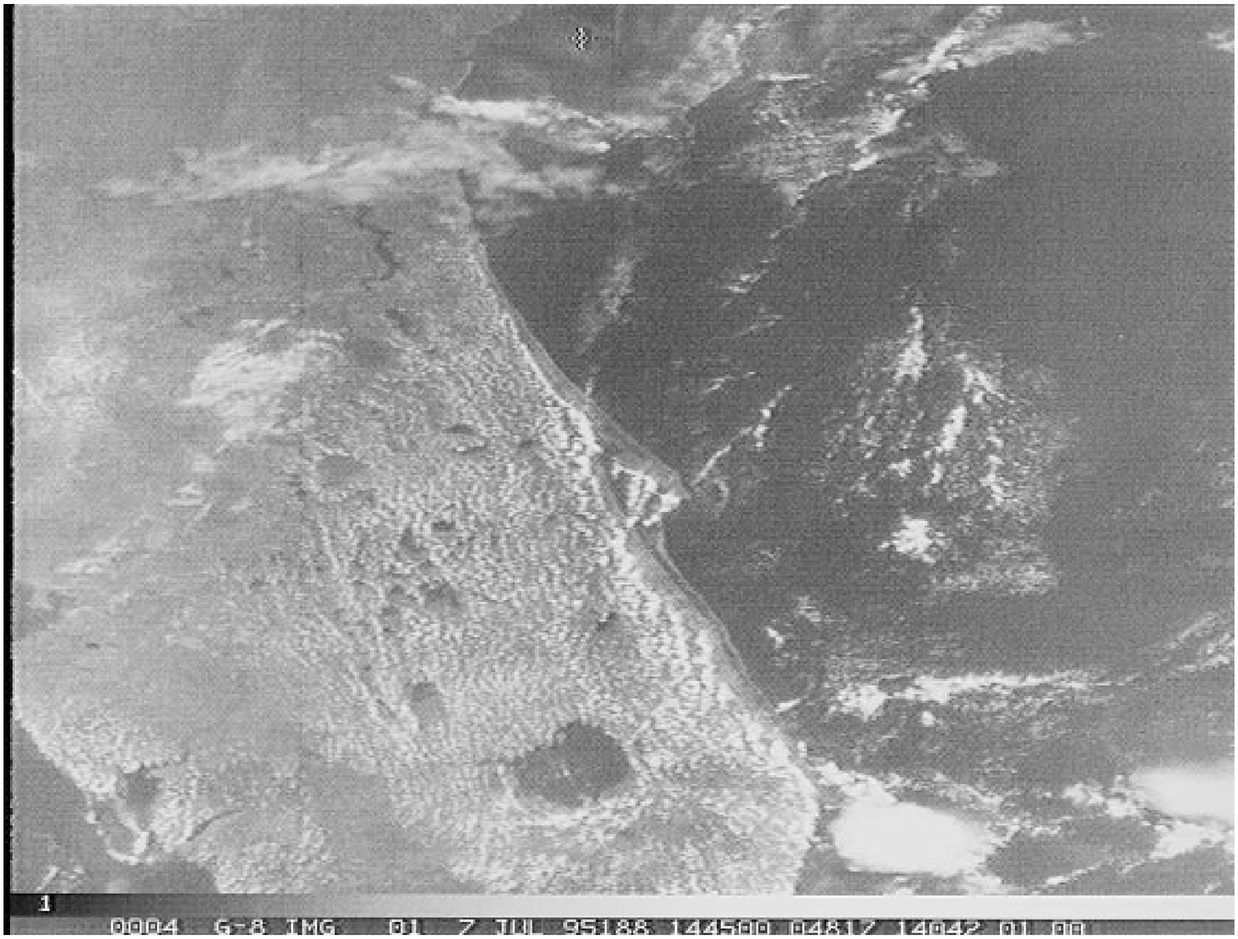


FIG. 12. *GOES-8* 1-km visible image, 1445 UTC 7 July 1995.

this go forecast, the flight director decided to ''waive'' the 2/10 observed cloud flight rule and deorbit. The shuttle landed safely at 1455 UTC 7 July 1995, with scattered clouds at 2700 ft covering 3/10 of the sky at landing time (Fig. 12).

3) STS-67 LANDING AT EDWARDS AFB (WINDS)

STS-67 (*Endeavor*) was scheduled to land at KSC on 17 March 1995. Showers and thunderstorms in the KSC area prevented a landing during all three KSC landing opportunities. Thus, *Endeavor*'s landing was waved-off and the shuttle and seven-person astronaut crew spent one more day in orbit. On 18 March 1995, showers and thunderstorms were forecast for the KSC area. SMG forecasters at the Mission Control Center in Houston coordinated with the National Severe Storms Forecast Center in Kansas City. This forecast coordination helped SMG convince the NASA flight control team and MMT that landing at KSC was not safe that day, and the decision was made to land at EDW. However, crosswinds were a prime weather concern at EDW for the 2047 UTC scheduled landing time. At the deorbit burn decision time, the peak crosswinds on EDW Runway 22 varied between 11 and 15 kt, just within the 15-kt crosswind limit. SMG forecasters assimilated weather information from a mesoscale network of wind towers, frequent weather balloon releases, and military weather observers at EDW, to accurately forecast that winds would remain within shuttle crosswind limits for the shuttle's touchdown time. SMG forecast experience with local wind circulations around the EDW lakebed runway complex (Hafele and Garner 1993) was critical in the development of this landing forecast and in the confidence of that forecast expressed to the flight director. EDW wind tower plots at the deorbit burn time (1923 UTC) and at landing time (Figs. 13a and 13b) indicate the variability of the EDW lakebed winds. *Endeavor* landed safely at 2047 UTC 18 March 1995. Surface crosswinds winds at landing time were 8 kt, well within crosswind limits.

5. Summary

The Spaceflight Meteorology Group is an integral part of the shuttle flight control team. SMG provides critical landing weather support to the Mission Control Center at JSC and the Space Shuttle Program. This support is quite

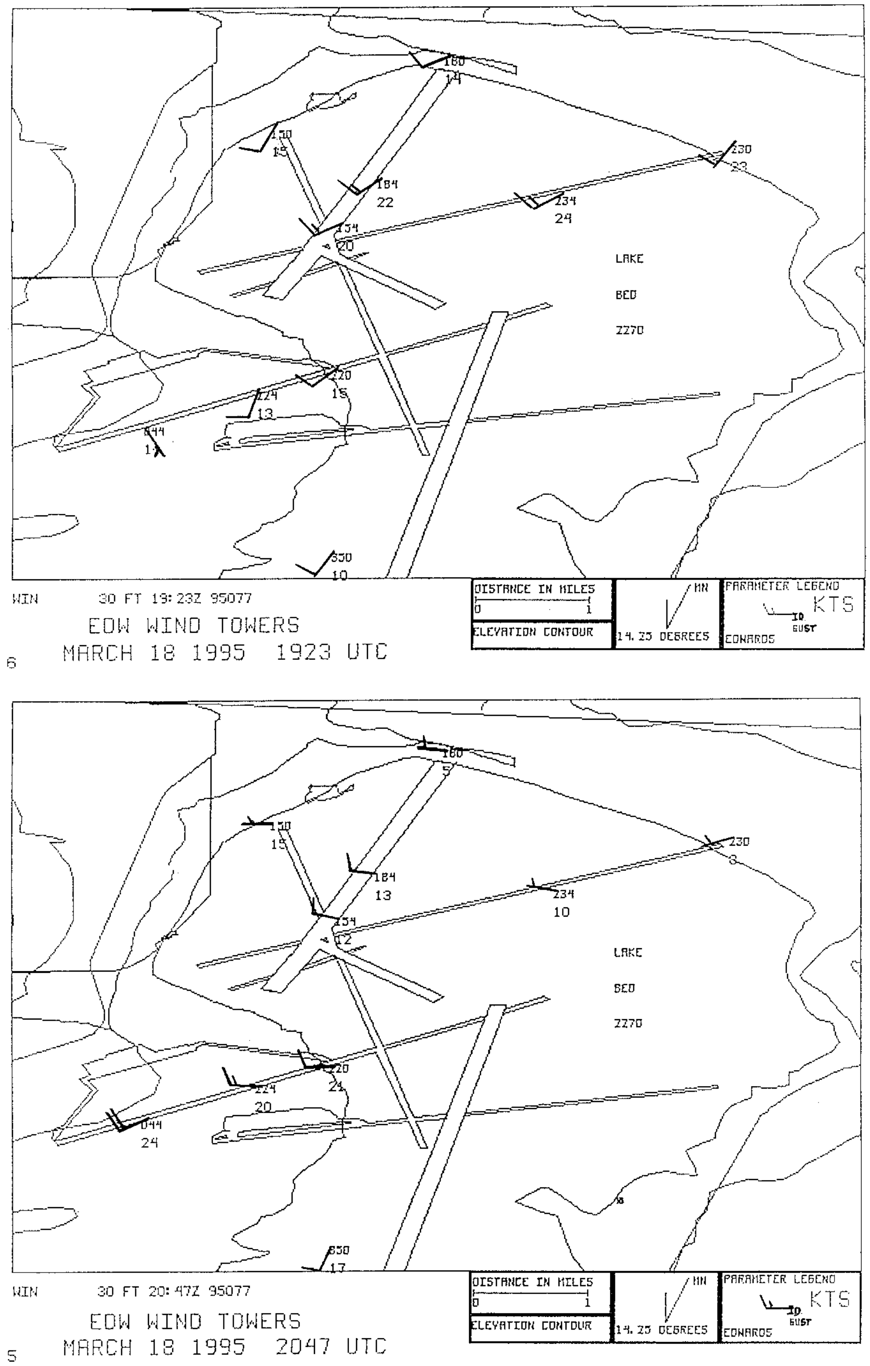


FIG. 13. Edward Air Force Base mesonet 30-ft wind tower data, (a) 1923 UTC 18 March 1995, and (b) 2047 UTC 18 March 1995.

complex and specialized. It requires a meteorologica1 team skilled and experienced in forecasting, computer technology, and understanding specific customer requirements. The ongoing challenge is to apply the latest developments in technology and meteorological knowledge to unique shuttle weather support requirements, in order to maintain and improve the quality of analyses, forecasts, and weather advice. This, in turn, will allow NASA to maintain and improve its ability to make safe, smart, and cost-effective weather-related shuttle launch and landing decisions.

6. Future work

SMG will be exploring and reviewing systems and techniques, including data assimilation models, for more effective integration of the steadily increasing volume of meteorological data. Also, in conjunction with NCEP and the Applied Meteorology Unit, SMG will continue to evaluate and eventually incorporate mesoscale models and ensemble forecast techniques (Tracton and Kalnay 1993) into its operations. These initiatives will occur in combination with ongoing case studies and evaluations of shuttle landing weather scenarios.

Other future work will focus on becoming more completely integrated into the Mission Control Center, facilitating increased two-way electronic transfer of weather and flight control information between SMG and the Flight Control Team. A new challenge is the very short (5–15 min) launch windows required for rendezvous with the Russian *Mir* space station and with the upcoming construction of the international space station. SMG will continue working with the flight control team and Space Shuttle Program to help evaluate and refine weather flight rules to maximize launch and landing opportunities and maintain a safe environment for shuttle abort and end-of-mission landings.

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APPENDIX

Acronym List

1st Day PLS	First-day primary landing sites
45WS	United States Air Force 45th Weather Squadron
AMU	Applied Meteorology Unit
AOA	Abort-once-around
AVN	Aviation model
CCAS	Cape Canaveral Air Station
DDS+	Domestic Data Service +
EDW	Edwards Air Force Base
ELS	Emergency landing sites
EOM	End-of-mission
GOES	Geostationary Orbiting Environmental Satellite
IDS	International Data Service
JSC	Johnson Space Center
KHGX	NWSO Houston/Galveston, Texas
KMLB	NWSO Melbourne, Florida
KSC	Kennedy Space Center
LCC	Launch Commit Criteria
LPLWS	Launch Pad Lightning Warning System
MASS	Mesoscale Atmospheric Simulation System
MCC	Mission Control Center
MECO	Man-engine cutoff
McIDAS	Man-Computer Interactive Direct Access System
MIDDS	Meteorological Interactive Data Display System
MMT	Mission Management Team
MRF	Medium-range forecast
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction
NGM	Nested Grid Model
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OSF	Operational Support Facility
PLS	On-orbit primary landing sites
PUP	Principal User Processor
RTLS	Return to launch site
RUC	Rapid update cycle
SLF	Shuttle Landing Facility
SMG	Spaceflight Meteorology Group
TAL	Transoceanic abort landing
TDU	Techniques Development Unit
UTC	Universal time coordinated
WSR-74C	Weather Surveillance Radar-74C
WSR-88D	Weather Surveillance Radar-88D
WSSH	White Sands Space Harbor

REFERENCES

Austin, G. L., A. Kilambi, A. Bellon, N. Leoutsarakos, A. Hausner, L. Trueman, and M. Ivanich, 1986: Rapid II: An operational, highspeed interactive analysis and display system for intensity radar data processing. Preprints, *Joint Sessions 23d Conf. on Radar Meteorology and Conf. on Cloud Physics,* Snowmass, CO, Amer. Meteor. Soc., 79–82

Bellue, D. G., 1993: Spaceflight Meteorology Group evolution of the daily simulation forecast verification effort. Preprints, *Fifth Int. Conf. on Aviation Weather Systems,* Atlanta, GA, Amer. Meteor. Soc., 372–375.

——, and T. W. Garner, 1995: Nowcasting for shuttle weather support during the STS-59 mission. Preprints, *Conf. on Aviation Weather Systems,* Dallas, TX, Amer. Meteor. Soc., 286–291.

——, and J. S. Tongue, 1995: Use of the WSR-88D for space shuttle weather support during the STS-57 and STS-51 missions. *Natl. Wea. Dig.,* **19**(3), 16–25.

——, K. B. Batson, and T. D. Oram, 1996: Forecasting upper winds for the space shuttle. Preprints, *12th Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, Atlanta, GA, Amer. Meteor. Soc., 256–260.

Boyd, B. F., W. P. Roeder, J. B. Lorens, D. S. Hazen, and J. W. Weems, 1995: Weather support to pre-launch operations at the Eastern

Range and Kennedy Space Center. Preprints, *Sixth Conf. on Aviation Weather Systems,* Dallas, TX, Amer. Meteor. Soc., 135–140.

Brody, F. C., 1993: Operations of the Spaceflight Meteorology Group. Preprints, *13th Conf. on Weather Analysis and Forecasting,* Vienna, VA, Amer. Meteor. Soc., 189–193.

Crum, T. D., and R. L. Alberty, 1993: The WSR-88D and the WSR-88D operational support facility. *Bull. Amer. Meteor. Soc.,* **74,** 1669–1687.

Ellrod, G. P., 1995: Advances in the detection and analysis of fog at night using GOES multispectral infrared imagery. *Wea. Forecasting,* **10,** 606–619.

Ernst, J. A., and F. J. Merceret, 1995: The Applied Meteorology Unit: A tri-agency applications development facility supporting the space shuttle. Preprints, *Sixth Conf. on Aviation Weather Systems,* Dallas, TX, Amer. Meteor. Soc., 266–269.

Hafele, G. M., and D. J. Haller, 1991: Tools used to forecast weather at TAL sites during STS-41. Preprints, *Seventh Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology,* New Orleans, LA, Amer. Meteor. Soc., 36–41.

——, and T. W. Garner, 1993: Planned use of a meteorological mesonetwork to assist forecasting the weather conditions at Edwards Air Force Base for space shuttle landings. Preprints, *Fifth Int. Conf. on Aviation Weather Systems,* Atlanta, GA, Amer. Meteor. Soc., 35–39.

Heckman, S. T., M. W. Maier, W. P. Roeder, J. B. Lorens, and B. F. Boyd, 1995: The operational use of a boundary layer profiler network at the Eastern Range and Kennedy Space Center. Preprints, *27th Conf. on Radar Meteorology,* Vail, CO, Amer. Meteor. Soc., 346–348.

Hermes, L. G., 1993: Chaff observations with WSR-88D: Examples and operational impacts. Preprints, *Second NWS National Aviation Weather Workshop,* Boulder, CO, National Weather Service, 43–48.

Krider, E. P., R. C. Noggle, and M. A. Uman, 1976: A gated, wideband magnetic direction finder for lightning return strokes. *J. Appl. Meteor.,* **15,** 301–306.

Maier, M. W., L. M. Maier, and C. Lennon, 1995: Lightning detection and location systems for spacelift operations. Preprints, *Sixth Conf. on Aviation Weather Systems,* Dallas, TX, Amer. Meteor. Soc., 292–297.

Manobianco, J. T., J. W. Zack, and G. E. Taylor, 1996: Workstation-based real-time mesoscale modeling designed for weather support to operations at the Kennedy Space Center and Cape Canaveral Air Station. *Bull. Amer. Meteor. Soc.,* **77,** 653–672.

NASA/JSC, 1997a: NASA Operational Shuttle Flight Rules (NSTS 12820), Final June 6, 1996, PCN-4 May 1, 1997, Vol. A, section 2.1.1-6. NASA/Johnson Space Center, 2-11–2-33. [Available from JSC/DA8, Houston, TX 77058.]

——, 1997b: NASA Space Shuttle Launch Commit Criteria and Background (NSTS 16007), Chapter 4, May 15, 1997; Chapter 5, August 28, 1996. NASA/Kennedy Space Center, 4-1–4-15 and 5-1–5-7. [Available from JSC/AP4, Houston, TX 77058.]

Plummer, D. W., 1989: Diagnostic and forecast graphics products at NMC using high frequency model output. *Wea. Forecasting,* **4,** 83–89.

Roeder, W. P., 1995: Operational impacts and identification of chaff on weather radar. Preprints, *27th Conf. on Radar Meteorology,* Vail, CO, Amer. Meteor. Soc., 373–375.

Rotzoll, D. A., S. J. Cunningham, and E. K. Hogan, 1990: Evolution of MIDDS II in JSC space shuttle operations. Preprints, *Seventh Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology,* New Orleans, LA, Amer. Meteor. Soc., 48–53.

Suomi, V. E., R. Fox, S. S. Limaye, and W. L. Smith, 1983: McIDAS III: A modern interactive data access and analysis system. *J. Climate Appl. Meteor.,* **22,** 766–778.

Tracton, M. S., and E. Kalnay, 1993: Operational ensemble prediction at the National Meteorological Center: Practical aspects. *Wea. Forecasting,* **8,** 379–398.

Young, J. T., and R. J. Fox, 1994: Future plans for McIDAS workstations. Preprints, *Workshop on Meteorological Operation Systems,* Reading, United Kingdom, ECMWF, 240–247.