P7.1 WEATHER SUPPORT FOR THE CASSINI MISSION TO SATURN

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1. INTRODUCTION

The Air Force's 45th Weather Squadron (45 WS) provides comprehensive weather service to the Eastern Range (ER) and the Kennedy Space Center (KSC) for America's space program. These services include weather support for personnel safety and resource protection, pre-launch ground processing, day-of-launch, post-launch, and special operations for more than 30 space launches per year. Launch customers include the Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and commercial companies.

Missions to the outer planets cannot rely on solar power, and thus require radioactive material for power and/or heat. Use of radioactive material onboard requires additional levels of safety oversight from the earliest planning through launch countdown. Prelaunch planning for this type of mission is an interagency responsibility and is accomplished via the Interagency Nuclear Safety Review Panel (INSRP). The day-of-launch radiological release support is the responsibility of the Department of Energy (DoE) and is accomplished by DoE's designated representative with the cooperation of DoD's 45 WS. This paper summarizes weather support for one such mission, the Cassini probe to Saturn.

2. THE CASSINI MISSION

Cassini is a cooperative endeavor of NASA, the European Space Agency (ESA) and the Agenzia Spaziale Italiana (Italian Space Agency). The mission sent a sophisticated spacecraft, equipped with 12 scientific experiments, to orbit Saturn for a four-year period to study the Saturnian system. The ESA-built Huygens probe will parachute into the thick atmosphere of Titan (Saturn's largest moon) carrying another six scientific instrument packages.

Cassini was launched aboard a Titan-IVB/Centaur at 4:43 a.m. EDT, 15 October 1997. This began a 6.7-year journey to arrive July 2004 at Saturn for a four-year scientific exploration.

Deep space missions require radioactive materials for heat and electrical power. Payload heat was supplied by 129 Radioisotope Heat Units (RHUs), each containing 2.56 gm of Plutonium-238 (Pu-238). The electrical power was supplied by three Radioisotope Thermoelectric Generators (RTGs) (Figures 1 and 2), containing a total of 32,700 gm of Pu-238.

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The RHUs and RTGs were designed to withstand almost any launch accident, so that under most conditions, no nuclear material would be released. In rare cases where a release might occur, the total amount of released Pu-238 was predicted to be between 0.56 gm and 360.14 gm, depending on the accident scenario.

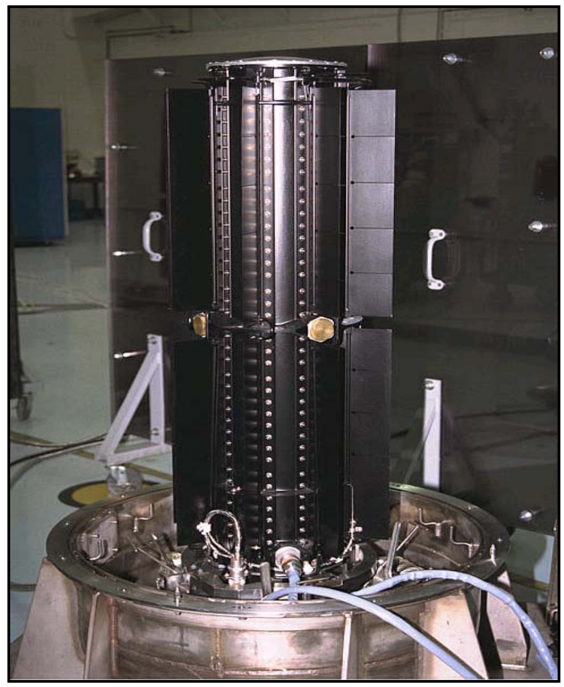

Figure 1. Radioisotope Thermoelectric Generator

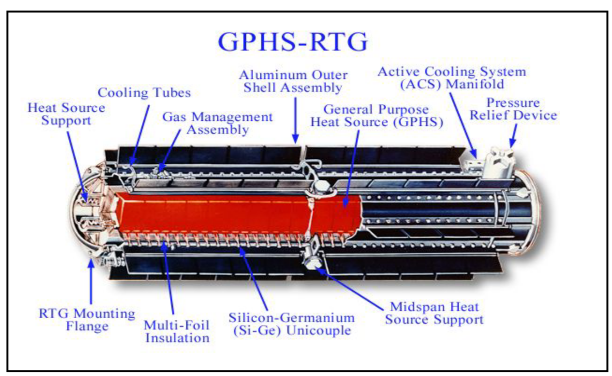

Figure 2. Radioisotope Thermoelectric Generator (cut away view)

Cassini-Huygens (Figure 3) is a massive spacecraft. It is carefully designed to brake into Saturn's orbit, as well as being loaded with an array of powerful instruments, cameras, and sensors that will optimize the exploration of Saturn's vast, distant system. The spacecraft consists of two elements: the Cassini orbiter and the Huygens probe.

The mass of the Cassini spacecraft, and the distance to Saturn, required the use of America's most powerful launch vehicle – the Titan-IV/Centaur. Figure 4 depicts the Titan-IVB vehicle with its 66-foot-tall, 17-foot-wide payload fairing on top, encasing the Cassini's Huygens probe and Centaur stage. Even with this launch vehicle and booster, there was not enough energy to send the spacecraft directly to Saturn. The mission designers used a technique called "gravity assist" to supply the added energy. Gravity assist works because of the mutual gravitational pull between a moving planet and a spacecraft. The planet, of course, pulls on the spacecraft. But the spacecraft's own mass also pulls on the planet, permitting an exchange of energy. Since the mass of the spacecraft is so much less than the planet, the spacecraft gains considerable velocity, while the loss to the planet is infinitesimal. The Cassini spacecraft received four planetary gravity assists via close flybys of Venus (twice), Earth, and Jupiter (Figure 5).

Cassini-Huygens is scheduled to reach Saturn and its moons in 2004. There the spacecraft will orbit throughout the system for four years; beaming home valuable data that will help us understand the vast Saturnian region. Huygens will enter the murky atmosphere of Titan, Saturn's biggest moon, and eventually descend via parachute onto its mysterious surface. The Huygens probe will send its measurements and images to Cassini, which will then beam them back to Earth. Figures 6 shows the arrival and initial orbit around Saturn, while Figure 7 depicts sample orbits during the four-year mission.

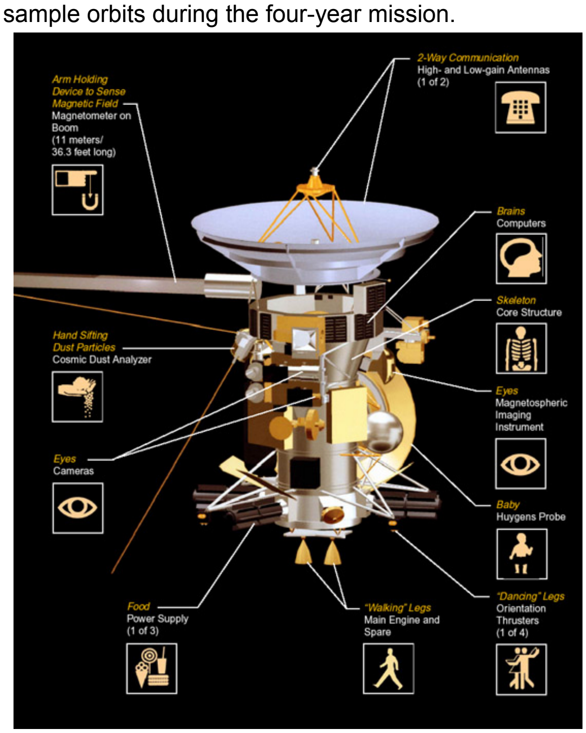

Figure 3. Cassini-Huygens Spacecraft

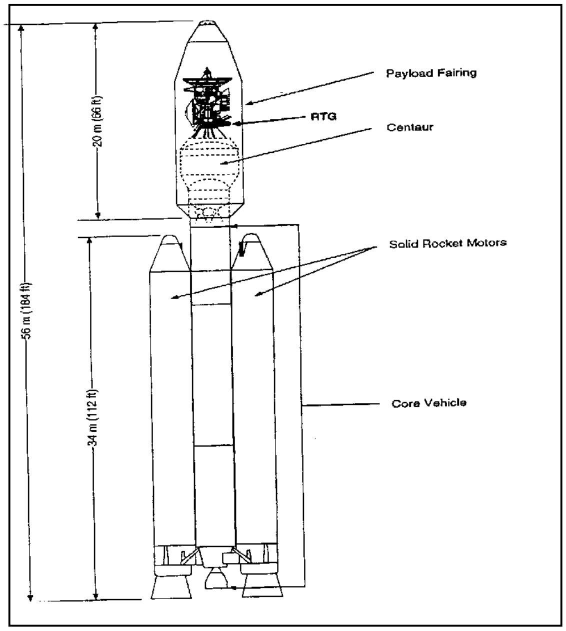

Figure 4. Titan-IVB/Centaur Schematic

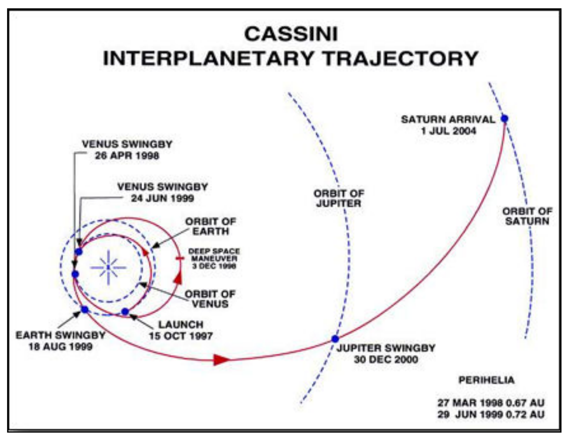

Figure 5. Cassini Trajectory

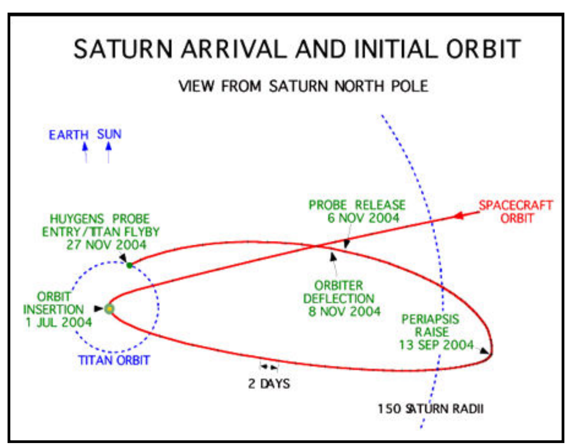

Figure 6. Arrival and Initial Orbit

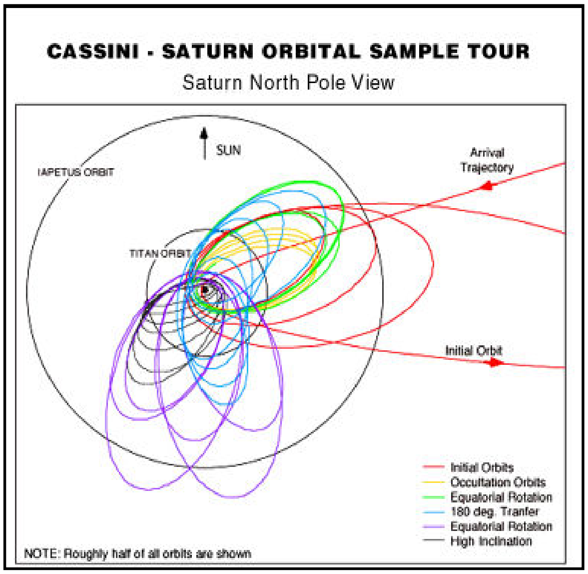

Figure 7. Sample Orbits

3. DOD SUPPORT TO CASSINI

3.1 ER Preparations for Cassini

All space launches with radioactive material onboard require Environmental Impact Statements (by the National Environmental Policy Act and NASA policy). NASA completed the Environmental Impact Statement in June 1995 and a supplement in June 1997. Consistent with long-standing Presidential policy, the DoE prepared a comprehensive Safety Analysis Report over a seven-year period. The Interagency Nuclear Safety Review Panel (INSRP) confirmed the safety analysis conducted for the mission was comprehensive and thorough. The INSRP is a Presidential appointed panel, with representatives from DoE, NASA, DoD, the Environmental Protection Agency (EPA), and a technical advisor from the Nuclear Regulatory Commission. Over 50 scientific experts from government, academia and industry supported this panel.

Other than serving on INSRP, the 45 WS's main effort in preparation for Cassini was in improving weather systems. The Air Force and NASA, over the years, have developed an extensive meteorological instrumentation network for launch support. That network of meteorological sensors on the ER is described in detail by Harms et al. (2003).

The single most important weather system improvement which directly benefited the Cassini mission was installation of a network of five 915 MHz boundary layer Doppler Radar Wind Profilers (DRWP) with Radio Acoustic Sounding Systems (RASS) (Figure 8). This DRWP/RASS network measures wind and virtual temperature in the lower three kilometers of the atmosphere. This information is critical to predict diffusion and deposition in case of an accident. Data from that network, a 50 Mhz DRWP, and the ER's meteorological tower network (Figure 9), along with observed and forecast upper-air soundings, were provided to the Atmospheric Release Advisory Capability (ARAC) via a Meteorological Interactive Data Display System (MIDDS) connection. (See following paragraph on DoE support).

For launch support, the upper-air system is the most critical single weather system on the ER. The high cost of space vehicles and payloads demands careful monitoring and evaluation of vehicle loading caused by in-flight winds. The rocket must counter-steer against the actual winds versus the planned winds to keep on the proper trajectory for correct orbital insertion. If the differences between actual and planned winds are too large, the rocket can counter-steer so hard it can destroy itself. A group of aeronautical engineers, referred to as the LOADS community, analyzes observed winds prior to launch to ensure this does not happen. Modern launch programs, including Shuttle and Titan-IV, develop a steering profile from actual observations and uplink to the vehicle as close as possible to launch. Essentially the launch vehicle's payload capability must be reduced by the loading uncertainties, thus reducing launch productivity. Various authors such as Smith and Adelfang (1992), Adelfang et al. (1993), and Wilfong, et al. (1996) have described use of upper air wind data, its use for loads and steering, and the impact of upper air variability on launch operations. The ER upper-air system, as described by Wilfong et al. (1996) has recently been replaced by the Automated Meteorological Profiling System (AMPS), which uses the Global Positioning System (GPS) as described by Divers et al. (2000).

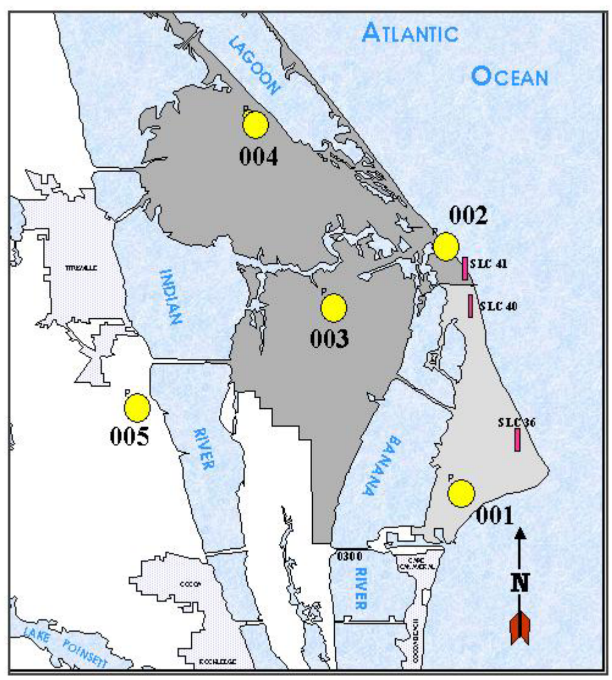

Figure 8. 915 DRWPs

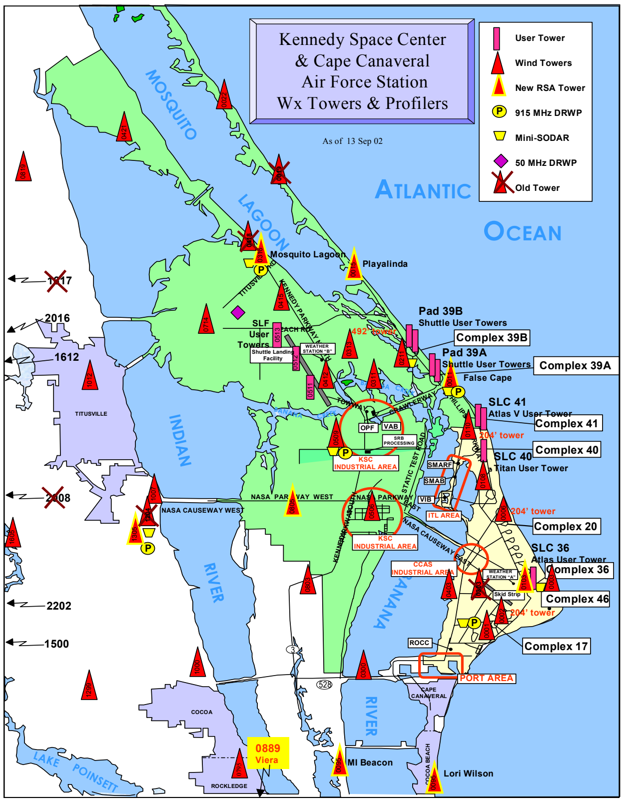

Figure 9. Wind Tower Locations

3.2 ER Operational Support to Cassini

The day-of-launch radiological release support is the responsibility of the Department of Energy (DoE) and was accomplished with the cooperation of DoD's 45 WS. Actual ER weather support for the Saturn mission was two pronged – support to the launch vehicle and support to the spacecraft. Spacecraft support leading up to launch countdown is shown in Table I.

Support to the launch vehicle was standard for a Titan vehicle except for providing data to the DoE and the local Radiological Control Center. The typical 45 WS day-of-launch support has been described by Boyd et al. (1993), and Taylor et al. (1998). This support, which 45 WS is directly responsible for, includes: evaluation of weather Launch Commit Criteria (LCC), including the Lightning LCCs (Roeder et al., 1999a) and User LCC for low level wind, ceiling and visibility; and observation and forecast of the weather (Boyd et al., 1998). The 45 WS also advises on weather impacts on launch decisions for which other organizations are responsible, such as: Range Safety for toxic dispersion (Parks et al., 1996), sonic blast (Boyd et al., 2000), and debris fallout predictions (Boyd et al., 1999); and the LOADS engineers (Boyd et al., 1997),

Most of the Lightning LCC are for triggered lightning, where the launching rocket itself causes the electric discharge. Triggered lightning is caused by the rocket and its electrically conductive exhaust plum passing through a sufficiently strong pre-existing electric field. The exhaust plume essentially compresses the electric field until the breakdown potential voltage of air is exceeded. While the threat from triggered lightning was identified in the Apollo Program (Krider, et al., 1974), the lightning LCCs are continually refined (Roeder et al., 1999b).

The LCC protect primarily against electric charge generated in the mixed solid-liquid phase of water (normally in the 0 to –20^{o} C layer), either directly at the charge generation site, or advected elsewhere after charge generation, e.g. via anvil or debris clouds. The distinction between triggered and natural lightning is important. Ten of the eleven LCC are for triggered lightning. Even the one natural lightning rule is mostly for triggered lightning, due to charge deposition from the natural lightning, rather than the natural lightning bolt intercepting the rocket.

Many weather phenomena generate electric fields that are insufficient for natural lightning, but can cause triggered lightning when those fields are compressed by the exhaust plume. These weather phenomena include cumulus clouds reaching cold enough temperatures and thick stratus clouds of sufficient thickness at the right temperature levels, among others. Some phenomena can generate higher electric fields that occur over a shallow depth and are not a triggered lightning threat. These, phenomena include: fog, surf, raindrop fracturing, power lines, and the 'Sunrise Effect' (Marshall et al, 1999).

TABLE I
Spacecraft Prelaunch Support

EVENT	DATE
Cassini-Huygens Spacecraft Arrive KSC	21 Apr
Integrated Training Simulation (ITS) 1A	22 May
Integrated Training Simulation (ITS) 1B	23 May
Cassini transport SAEF to PHSF	27 May
Integrated Crew Exercise (ICE) 2A	9 Jul
Integrated Crew Exercise (ICE) 2B	10 Jul
First Terminal Countdown Demonstration (TCD)	5 Aug
Second TCD	20 Aug
Cassini transport and lift/mate KSC/PHSF to Launch Complex 40	28 Aug
Cassini demate & transport LC40 to KSC/PHSF	5-7 Sep
Mission Dress Rehearsal (MDR)	9-10 Sep
Cassini transport and lift/mate KSC/PHSF to Launch Complex 40	15-16 Sep
Propellant load	4-7 Oct
NASA Cassini Launch Readiness Review	9 Oct
AF Launch & Cassini Flight Readiness Review	10 Oct

In addition to the LCCs, the user also had weather launch constraints (Table II), which 45 WS launch weather officers were required to forecast and monitor. These User LCC include temperature due to fuel sensitivities; low-level wind, so the rocket will not be blown into the launch pad; ceiling and visibility for optical tracking, and a sensible weather forecast to ensure weather conditions are safe prior to exposing the rocket to the environment.

TABLE II
User Weather Constraints

ITEM	CONSTRAINT
Rain	No rain/virga along flight path at or above 3500 feet
Cloud/Fog	Ceiling ≥ 3000 feet, Visibility ≥ 5 miles
Wind for MST rollback:	Forecast peak wind <60 kts @ 162 feet Observed peak wind < 38 kts @ 162 feet for 30 min prior to MST rollback
Temperature	≥35°F for 24 hours prior to MST rollback Between 35°F and 100°F from MST rollback until launch >50°F for 4 hours prior to launch

The upper-air observation requirements (Table III) were very demanding during the launch countdown, in part because of competing needs of the many customers -- forecasting, safety, steering, and loads (Boyd et al. (1997)).

The mission was originally scheduled for launch on 6 October 1997. It was rescheduled for 13 October prior to entering the launch countdown, when the payload was required to be returned to the Payload Hazardous Servicing Facility (PHSF) due to thermal insulation damage inside the Huygens probe from a higher than appropriate flow rate of conditioned air (Table I). This required further internal inspections, insulation repair, and probe cleaning.

The rescheduled launch of 13 October entered the launch countdown, but was scrubbed late in the launch window. The scrub was due to debris footprint violations. The launch winds were near constraint limits and the debris footprint violations were due primarily to deviation from climatology with a strong jet streak, 90 - 95 knots at 42,000 - 45,000 feet, from the northeast. This jet streak was associated with a minor disturbance rotating around the periphery of the upper level high over the Southeastern United States. Scrub for debris is a rare occurrence at the ER, where most strong upper air winds are westerly, which blow debris out over the Atlantic Ocean.

The second launch attempt went without incident, and was successfully launched 15 October 1997 on its long journey (Figure 10).

TABLE III
Balloon Release Schedule

TIME	PURPOSE	TYPE
L-24:00 hours	Forecasting, Steering, Safety	Rawinsonde/ Windsonde
L-8:30 hours	Forecasting (Fcst)	Rawinsonde
L-5:10 hours	Steering, Fcst.	Windsonde
L-3:40 hours	Steering, Safety, Fcst.	Windsonde
L-3:10 hours	Loads	Jimsphere
L-2:40 hours	Steering, Loads, Safety, Fcst.	Windsonde
L-2:10 hours	Loads	Jimsphere
L-1:40 hours	Steering, Loads, Safety, Fcst.	Windsonde
L-1:10 hours	Loads	Jimsphere
L-0:40 hours	Steering, Loads, Safety, Fcst.	Windsonde
L-0:10 hours	Loads (in case of delay)	Jimsphere
L+0:20 hours	Loads (in case of delay), Fcst.	Windsonde

Figure 10. Cassini Launch October 15, 1997

4. DOE SUPPORT TO CASSINI

4.1 Atmospheric Release Advisory Capability (ARAC)

The ARAC mission is to provide timely and credible advisories for radiological (and other) hazardous releases to the atmosphere. The ARAC system simulates the release of some material in the atmosphere and predicts its movement downwind. The system calculates the consequences to health due to the release, based on known characteristics of the material (Pace, 1998).

ARAC has been designed to respond in near-real-time to releases anywhere worldwide. The flexible ARAC system has been used for many types of actual or exercise events (nuclear power plants, weapons, volcanoes, missile launches, oil fires, and many others). For non-routine applications, such as support to space launches, ARAC's support is improved if equipment is deployed and plans are made before any potential release.

The ARAC system (Sullivan et al., 1993) uses topographical and meteorological data to generate a time-varying series of three-dimensional mass adjusted wind fields, which are used to drive the Atmospheric Diffusion Particle-In-Cell (ADPIC) Lagrangian particle dispersion model. ADPIC is a three-dimensional model which accounts for the effects of spatial and temporal variation of mean wind and turbulence, gravitational settling, dry and wet deposition, and initial plume buoyancy and momentum.

ARAC personnel use horizontal and vertical cross-sections through the plume along with other displays to study and evaluate the structure of the plume, in order to decide whether the models are working optimally. The ARAC models have been extensively evaluated during many field tracer studies, and the results show the system is highly accurate when the source term is well known and the meteorological conditions are well represented (Foster, et al., 1990).

4.2 ARAC Cassini Support

For the Cassini launch, four ARAC scientists deployed to Florida, along with three ARAC computer systems (Pace, 1998). All model calculations were done at the Lawrence Livermore National Laboratory (LLNL), but the on-site personnel assisted in interpretation of the model results and acted as interfaces to the staff at LLNL, describing current conditions and channeling requests for support. To use all the data available from the ER/KSC area, ARAC developed procedures to retrieve the data from MIDDS automatically several times each hour, and created a new software package allowing display and editing of the tower, balloon, and profiler data retrieved from MIDDS. Using this package, ARAC personnel performed quality control of the MIDDS data before their use in the ARAC models. The MIDDS data retrieval and all communications between LLNL and the deployed personnel and equipment were done over dedicated communications circuits provided by DOE's Remote Sensing Laboratory (RSL). The 45 WS also supplied ARAC with forecasted upper air data (soundings). The full set of data from the MIDDS system provided excellent spatial (horizontal and vertical) and temporal resolution.

For Cassini, ARAC made its first operational use of its own execution of the Navy Operational Regional Atmospheric Prediction System (NORAPS), a prognostic model. NORAPS was developed by the Naval Research Laboratory, has been used operationally for several years at the Fleet Numerical Meteorology and Oceanography Center, and was supplied to ARAC through an interagency support agreement.

ARAC had access to four types of meteorological data: forecasted soundings; MIDDS reports of local sensors; NORAPS output; and surface and upper air observations from the region, which ARAC collected from the Air Force Weather Agency. ARAC has automated procedures to retrieve, store, and use each of these types, and can run its models with these sources individually or in any combination. Except for changes to accommodate the new meteorological data sources, ARAC used its existing, well-tested, validated models to support Cassini (Pace, 1998).

5. SUMMARY

Space launches with radioactive materials onboard require special weather support to minimize risk to the general public. The Cassini mission to Saturn is one example of such a launch. The special weather support required by this mission is discussed, and is typical of support for all missions with significant radioactive material.

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