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Clouds with supercooled liquid water constitute a significant aviation hazard because of the potential risk of aircraft icing. Icing reduces rate of lift, rate of climb, and fuel efficiency while increasing drag, stalling speed, weight, and power requirements. Indirectly, icing also exacts a penalty because on board icing detection/removal equipment may be required at the expense of other payload and because icing conditions may restrict launch/recovery or possible flight paths. All of these considerations can be of increased importance for unmanned aerial vehicle (UAV) operations because of the unique design features of some UAVs and because of the extra burden placed on autonomous control systems. Therefore, UAV operations will require strong icing forecast support and remote icing detector systems at the vehicle bases and possibly on the vehicles themselves. High flying long endurance UAVs will be able to fly above icing levels but are at special risk in ascending/descending through icing layers due to the degradation icing causes to the highly optimized wing shape of such vehicles. Low flying short endurance vehicles do not have such sensitive wing shapes but may not be able to fly above all icing layers. The high flyers may be able to ascend/descend over their bases and thus require remote sensors only at the bases, whereas low flyers may require on board sensors when they are out of base sensor range. A brief overview of the icing problem for UAVs will be given along with proposed solutions and potential needs, including improved forecasting and reliable compact remote sensors.

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IMPACT OF ICING ON UNMANNED AERIAL VEHICLE (UAV) OPERATIONS

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ABSTRACT

Clouds with supercooled liquid water constitute a significant aviation hazard because of the potential risk of aircraft icing. Icing reduces rate of lift, rate of climb, and fuel efficiency while increasing drag, stalling speed, weight, and power requirements. Indirectly, icing also exacts a penalty because on board icing detection/removal equipment may be required at the expense of other payload and because icing conditions may restrict launch/recovery or possible flight paths. All of these considerations can be of increased importance for unmanned aerial vehicle (UAV) operations because of the unique design features of some UAVs and because of the extra burden placed on autonomous control systems. Therefore, UAV operations will require strong icing forecast support and remote icing detector systems at the vehicle bases and possibly on the vehicles themselves. High flying long endurance UAVs will be able to fly above icing levels but are at special risk in ascending/descending through icing layers due to the degradation icing causes to the highly optimized wing shape of such vehicles. Low flying short endurance vehicles do not have such sensitive wing shapes but may not be able to fly above all icing layers. The high flyers may be able to ascend/descend over their bases and thus require remote sensors only at the bases, whereas low flyers may require on board sensors when they are out of base sensor range. A brief overview of the icing problem for UAVs will be given along with proposed solutions and potential needs, including improved forecasting and reliable compact remote sensors.

1. INTRODUCTION

One of the most obvious ways in which clouds impact DoD systems and operations is through the effects of cloud induced icing on aircraft performance and related warfare missions. Due to the complex nature of the icing environment, the dependence of ice accretion on aircraft parameters, and the dependence of icing risk on flight profiles, the problem of coping with aviation icing is very difficult to treat in an operational setting with the desired accuracy and timeliness. Some of the unique features of UAVs, such as optimized air foils and increased dependence on autonomous systems, further complicate the icing problem. Fortunately, recent improvements in the understanding of cloud physics and ice accretion plus improved instrumentation promise some significant advances in the attempt to minimize the effects of icing. This paper begins with a brief overview of the various UAV families, followed by a quick review of relevant icing characteristics and associated aerodynamic consequences. The coupling of icing properties and vehicle characteristics is underscored in a comparison of two different UAV systems. Finally, general conclusions are drawn about the icing problem for UAVs and possible strategies for coping with this hazard are indicated. It is also emphasized that the research community and UAV designers and users must cooperate together to ensure that researchers understand operational needs and that users understand the parameters and extent of the icing problem.

2. OVERVIEW OF UAV FAMILIES

2.1 VARIETY OF UAV VEHICLES AND MISSIONS

There are a wide variety of UAV vehicle concepts and missions, as indicated in Table 1, taken from the Master Plan (1989) of the Joint Program Office for UAVs. The great range in operating conditions and support personnel and resources will have a major impact on the level of icing severity faced by a particular UAV system and the appropriate resources available to reduce the icing impact. The overriding concern with respect to icing is to optimize mission capability. Ideally this requires environmental information for vehicle designers, incorporation of environmental inputs into the mission planner, and development of sensors and related algorithms. It should be noted that some UAV concepts may be of marginal value unless they can achieve all their design goals, which may be ambitious and often do not take environmental constraints into consideration.

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TABLE 1. UAV FAMILIES (FROM MASTER PLAN, 1989)

	CLOSE	SHORT (VALIDATED)	MEDIUM (VALIDATED)	ENDURANCE
OPERATIONAL NEEDS	RECON/SURV. TGT ACQ. TGT SPOT DISRUPTION AND DECEPTION	RECON/SURV. TGT ACQ. TGT SPOT MET. NBC. COMMAND & CONTROL DISRUPTION & DECEPTION	PRE AND POST STRIKE RECON FOR PREDESIGNATED TGT. MET	RECON/SURV. COMMAND & CONTROL TGT ACQ. MET. NBC
LAUNCH AND RECOVERY	LAND/SEA	LAND/SEA	AIR/LAND/SEA	LAND/SEA
RADIUS OF ACTION	TO 30 KM	TO 150 KM/300 KM	TO 650 KM	TO 300 KM
SPEED	NOT SPECIFIED	DASH > 90 LOITER < 90	550 KT < 20.000 FT .9 MACH > 20.000 FT	DASH/LOITER
ENDURANCE	1 TO 6 HRS	8 TO 12 HRS	2 HRS	24 HRS TO DAYS
INFO TIMELINESS	NEAR REAL-TIME	NEAR REAL-TIME	NEAR REAL-TIME/RECORD	NEAR REAL-TIME
SENSOR TYPE	IMAGING, JAMMER	IMINT. COMMRELAY. RADAR. SIGINT. MET. MASINT. DATA RELAY. JAM. TGT DESIGNATE	IMAGING	SIGINT. MET. COMM/ DATA RELAY. NBC. IMAGING. MASINT
AIR VEHICLE CONTROL	REMOTE & TETHERED	PREPROGRAMMED/ REMOTE	PREPROGRAMMED/REMOTE	PREPROGRAMMED/ REMOTE
GROUND STATION	MANPACKED/ HMMWV	VEHICLE & SHIP. REMOTE	JSIPS (PROCESSING)/ REMOTE CONTROL	VEHICLE & SHIP.
DATA LINK	WORLD WIDE/LOW-HIGH INTENSITY	WORLD WIDE/LOW-HIGH INTENSITY	JSIPS INTEROPERABLE	WORLD WIDE/LOW-HIGH INTENSITY
CREW SIZE	2	MINIMUM	MINIMUM	TBD

2.2 ENVIRONMENTAL VULNERABILITIES OF UAVS

Because UAVs are unmanned, the dominant concern with respect to environmental hazards is not crew safety but mission success. This will depend upon the environmental effects on three factors: 1) vehicle integrity and performance, 2) onboard sensor viability and 3) the autonomous systems on board the vehicle. Note that the last factor is unique to UAVs. One example of an environmental hazard is icing. The icing problem has three components: 1) icing characteristics (which are a function of the local physics and meteorology), 2) aerodynamic effects (which are a function of the airfoil, vehicle speed, and duration of flight in icing conditions) and 3) vehicle operations (which depend on the mission profile). The last two components depend on the specific UAV and mission but require knowing the first component accurately.

3. REVIEW OF ATMOSPHERIC ICING PROPERTIES

3.1 GENERAL COMMENTS ON ICING ENVIRONMENT

The potential for icing exists when there is an extended volume in the atmosphere containing supercooled liquid water (SLW). Such an environment can come about in a variety of ways, as indicated in Fig. 1, adapted from Westwater and Kropfli (1989). Such situations are very common in the first 10 km in the atmosphere. Above that height the air is generally too cold and too dry for SLW to exist in significant amounts. The main point for UAVs is that they can readily encounter icing conditions in the lower atmosphere.

Unfortunately, while it is clear that icing represents a definite aviation hazard, it is by no means easy to forecast. It is a very complex phenomenon whose physics is not fully understood, depending on a number of variables, many of which have highly nonlinear relationships. Compounding the problem is the fact that the usual observations used in forecasting are widely separated in space and time. Worse, some of the most crucial parameters for forecasting, like liquid water, are not routinely measured. As a consequence, icing forecasts have not been very good and tend to be on the conservative side. From the mission planning point of view, this results in inefficient use of the available air space and restricted mission time. As a consequence, more accurate forecasts would be highly desirable for UAV operations. This in turn requires a better understanding of the icing phenomenon, better sensors to measure its relevant parameters, and improved understanding of the dependence of ice accretion on specific vehicle characteristics and performance.

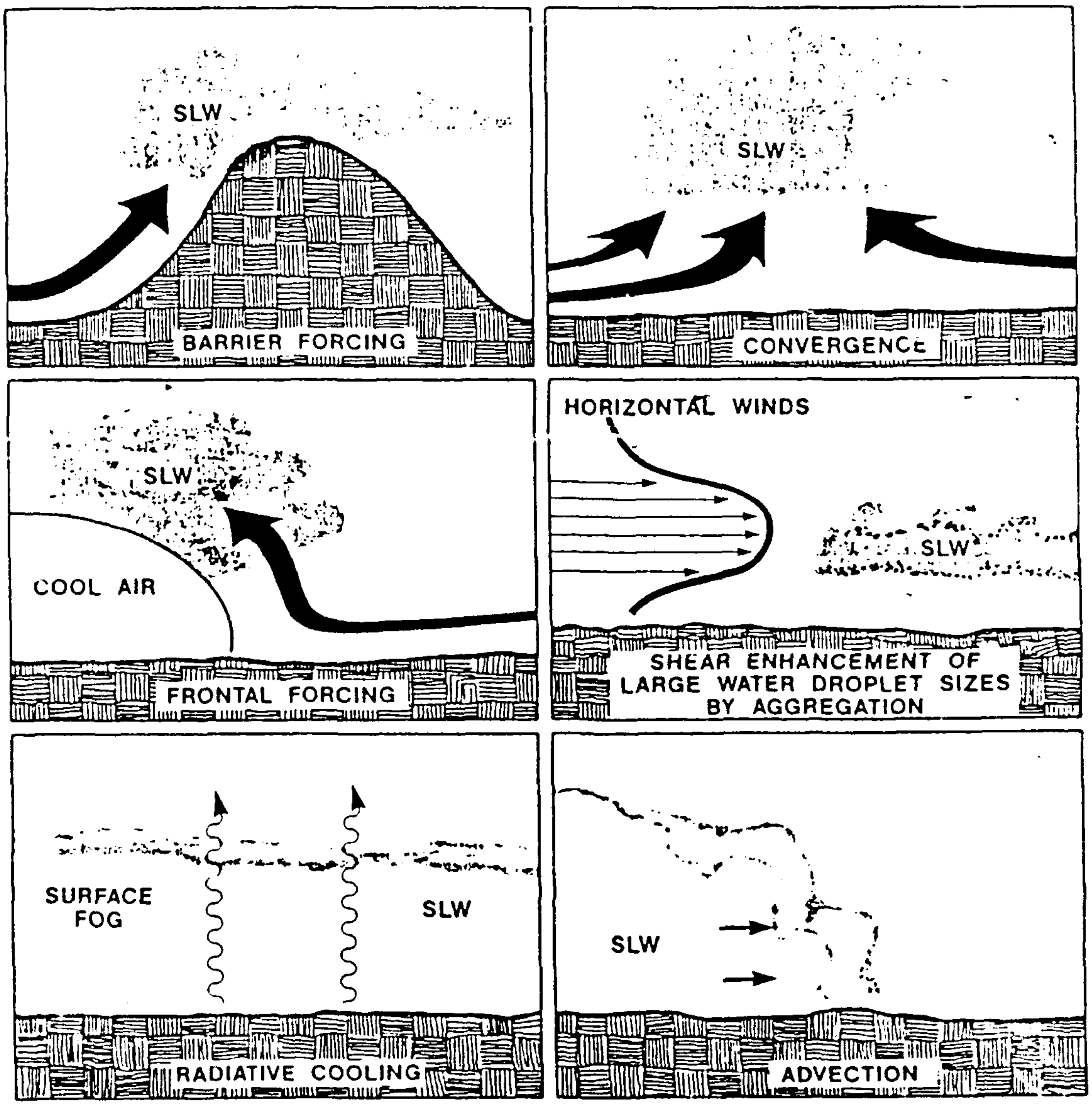

Figure 1. Atmospheric processes producing aircraft icing conditions (from Westwater and Kropfli, 1989).

3.2 CRITICAL ICING PARAMETERS

As delineated by Westwater and Kropfli (1989), icing potential depends upon a number of parameters, the most important of which are outside air temperature (OAT), liquid water content (LWC), and droplet size distribution. The most dangerous OAT is usually between 0 and -10 deg C. The higher the SLW usually the greater the icing severity, with values in excess of 0.1 g/m**3 considered potentially hazardous. As for droplet size distribution, the larger droplets represent a disproportionate share of the risk, with droplets having diameters between 30 and 400 microns being the most hazardous.

Other important icing parameters include cloud phase mix, small scale turbulence, water vapor flux, and cloud vertical motions. The relative amounts of liquid or ice in a cloud can reduce or enhance the icing potential and certainly complicate the forecasting problem. Small scale turbulence seems to affect ice accretion but in ways that are not fully understood yet. Naturally, increased water vapor flux increases SLW and so it is a useful variable to know. Within the cloud the larger droplets tend to form where the vertical motions are most intense and sustained.

From this catalogue of critical icing parameters it is obvious why it is so difficult to accurately predict icing hazards. Most of the parameters of interest are not even routinely measured, aside from the problem of coarse spacing of observations widely separated in time. Many of these variables can change significantly in short distances and in small intervals of time. Clearly, more continuous closer spaced observations, including parameters not normally available, are required to improve icing forecasts. As will be mentioned in Section 6, this is becoming increasingly possible through the use of remote sensors and satellite data.

4. EFFECTS OF ICING ON VEHICLE AERODYNAMICS

The effects of SLW on an aerial vehicle depend on three factors: 1) the aerodynamic shape of the airplane structure, 2) the vehicle s true airspeed, and 3) the length of time the vehicle is in the icing environment. The principal aerodynamic consequences are a decrease in lift and an increase in drag. This results in an increase in power required and stall speed but a decrease in speed margin, endurance, control, fuel efficiency and rate of climb. The types of icing encountered are (in order of decreasing frequency) rime, mixed, clear and frost. The impact of icing type on aerodynamics varies considerably, with clear ice representing the most hazardous condition, followed by mixed, rime, and then frost. Figure 2 (from Hansman, 1989) shows the effect of ice type on icing severity. A significant feature is that icing severity can undergo sudden transitions with slight changes in LWC or temperature, which underscores part of the challenge in accurate ice forecasting.

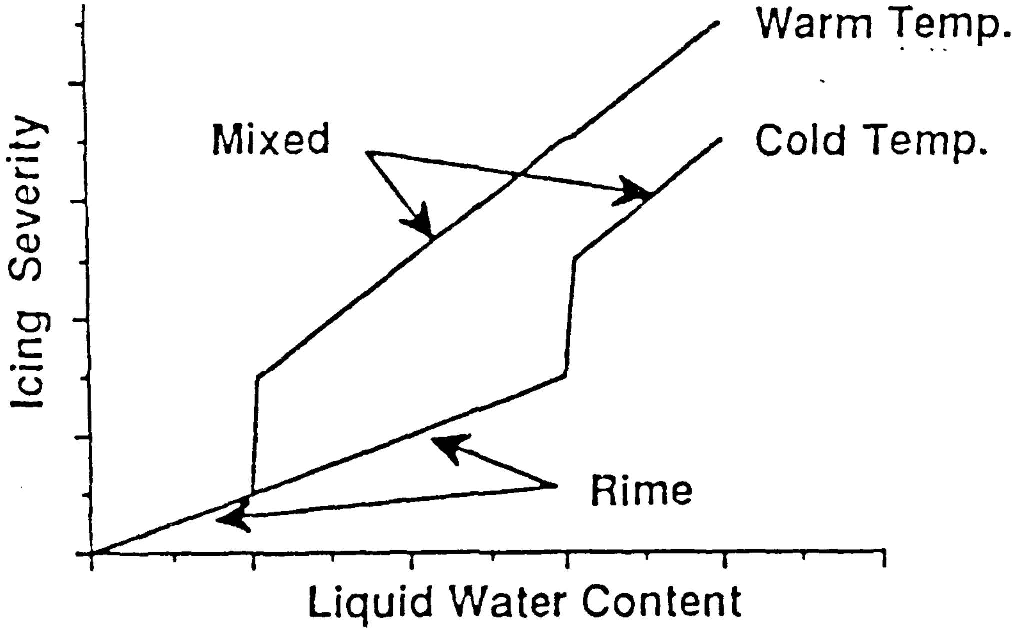

Figure 2. Icing severity (from Hansman, 1989).

A mundane example of how icing affects vehicle performance is in landing. Icing results in a higher stall speed, which means a higher landing speed. In addition, vehicle control may be degraded. Furthermore, the conditions leading to the icing could also result in a slippery runway. All these factors greatly increase the normal risk of landing a UAV.

5. EFFECTS OF MISSION PROFILE ON ICING SEVERITY

5.1 GENERAL COMMENTS

Because of the complex interplay of meteorological and physical parameters with aircraft characteristics to produce icing on the aircraft structure, the actual flight profile and mission are of crucial importance in determining the severity of icing. The altitude of flight, speed, rate of climb, mission duration, etc. will all be important. In this context it should be remembered that the success of some UAV missions is very dependent on being able to fly certain profiles. These preferred profiles may actually result in increased icing risk. It is important for system designers and operators to understand these environmental constraints in order to make informed tradeoff studies for their system's likelihood of success.

Of course, deicing equipment is available to free aircraft from accumulated ice and can allow aircraft to operate in some icing environments. Such equipment can be effective up to a certain point, but it also carries a penalty in weight, power required, increased system complexity, and increased system cost. Without such deicing equipment aircraft must avoid areas where icing exists or is predicted. This is the basic problem for UAVs because the lack of accurate forecasts unnecessarily restricts UAV flight profiles and times. This compromises the chances of mission success. Such limitations on UAV operational conditions seriously devalue these systems. All this can result without the UAV ever actually encountering icing. This is an example of the "virtual" impact icing can have on UAV operations.

The more obvious impact icing can have on UAV operations is from actual icing encounters. In this case, as noted above, there can be a serious degradation of vehicle performance, resulting in a diminished mission capability or even mission failure. Presumably such an encounter would not be deliberate and would most likely result from a poor forecast. To avoid such catastrophic consequences would require more conservative forecasts, resulting in the virtual impact discussed above.

Two points need to be stressed. First, vehicles that can't ascend or descend fast enough or cruise high enough face increased risk of icing exposure, Second, the icing problem imposes a special burden for the autonomous systems of some UAVs. Such systems would be preprogrammed to avoid forecasted or known hazards but would also have to recognize unpredicted hazards and know what corresponding action to take.

The importance of the UAV system/profile for determining the impact of icing will be illustrated with examples of two different types of UAV systems, a high altitude long endurance UAV and a UAV with cruise missile-like performance. The resources available to support each system are critical in determining what actions are feasible to protect the system from the hazard of icing.

5.2 HIGH ALTITUDE LONG ENDURANCE UAV

One concept for a UAV is for long range (several thousand nmi) extended surveillance (few days) from high altitudes (stratosphere). The critical design goal is endurance, and the most important contributing factor is weight. As a consequence, the desired vehicle must be very light weight with low power and a highly optimized laminar flow wing. Such a vehicle could be very vulnerable to ice accretion because of the resultant increase in drag and reduction in endurance and control. However, there should be no icing problem at cruise or loiter altitudes, except for ice accumulated earlier, because of the extreme coldness and dryness of the stratosphere. The icing problem for such a vehicle would exist on the ground or on takeoff/landing and ascent/descent due to the low rate of climb. Thus what would normally be a *fatal vulnerability to icing can be essentially avoided* through the following measures.

Operations must have very good forecasting support. For such large complex UAVs this should not be a problem if they are launched from well-equipped land bases with the usual array of weather sensors and with access to model outputs and satellite imagery. (Sensor requirements will be discussed in Section 6.) With the proper mix of remote sensors at the base, it should be possible to accurately forecast icing probability in the vicinity of the base. if the vehicle gains cruising altitude within range of the base sensors, then remote sensor support should only be necessary in the vicinity of the base. Once the vehicle is safely above the icing levels it can cruise out to its rendezvous with a Battle Group. If the vehicle does not descend through any icing layers before it is in range of the base remote sensors, then once again it should be able to minimize the icing danger. Great care should be exercised in keeping the vehicle clear of ice before takeoff. Note that if the vehicle has good icing forecast support, then it may not have to carry as large a reserve of fuel for landing, resulting in increased endurance. As an added precaution an on board deicer, such as the new lightweight piezoelectric systems, might be used.

5.3 LOW ALTITUDE HIGH SPEED UAV

This type of vehicle is rather like a non-lethal cruise missile with a range of a few hundred kilometers and a duration of a few hours. Because of the nature of its mission and to avoid detection, much of the time it will fly close to the ground or water, thereby increasing its icing risk. In fact, the icing problem may exist for most of its flight profile. Consequently, sensors at the launch site alone may not be adequate for icing detection and forecasting for the entire flight. To be sure, numerical model output and satellite data can be used for flight planning out of range of base sensors, but the lack of more detailed data would again lead to the problem of conservative forecasting. For this vehicle some sort of on board sensor system, either in situ or remote, for the detection of icing conditions may be desirable. This would in turn require corresponding autonomous systems for dealing with the sensor data and making the desired decisions to avoid the icing situation. In addition, an on board deicing system may also be necessary. A worrisome point is whether such UAV systems will have support personnel or resources to provide the necessary environmental data and decisions for adequate icing avoidance.

6. PROMISING DEVELOPMENTS

Fortunately for aviation safety there have been substantial recent developments in improved understanding of icing microphysics and ice accretion and encouraging developments in instrumentation. Furthermore, some large scale programs aimed at improving aviation icing forecasting and icing technology are poised to begin soon. These programs are primarily interested in air transport and general aviation safety, but there should be considerable benefits for UAV systems also.

In cloud physics there is now a better understanding of critical parameters for the occurrence of icing, leading to improved requirements for the appropriate sensors. This improved cloud physics understanding in turn has permitted improved aircraft ice accretion models, which, for example, require very accurate droplet size data for validation of droplet trajectory codes. Improved physics understanding also directly benefits icing forecasting by focusing on the meteorologically measurable quantities that are of most value in a forecast. The observations required for forecasting can now be done more continuously and at better spatial resolution through the use of satellites and local remote sensors. The large numerical weather prediction codes are more accurate over longer forecast times because of improved model physics and dynamics and faster computers with larger memories. Tactical decision aids have been developed for the remote user to assess local environmental risks like icing. Most of the above benefits assume the availability of some kind of advanced work station for assimilating data and outside model data for use in nowcasting and predictive services, like the PROFS workstation or the Navy's TESS workstation. As noted repeatedly above, the lack of such support seriously lowers the level of icing avoidance protection possible. Another point to stress is that to get the full benefit of the improvements in icing forecasting and technology, the forecasts should be aircraft specific for a given flight profile.

The advances in sensor technology have been particularly impressive. Figure 3 is taken from Westwater and Kropfli (1989) and shows the wide range of sensors that can contribute useful research information for predicting aircraft effects. Not all the sensors would be useful in an operational setting, for example, the upward pointing airborne MW radiometer. The main point, though, which is true for both research and operational needs, is that a suite of complementary instruments can act in effect as a virtual icing sensor. Operational constraints would then determine how much of the power of such a virtual sensor would be available for mission support. Clearly, high asset missions would require more such support. An interesting challenge for icing technologists would be to determine the minimum suite of sensors required for support at a risk level that the UAV system can tolerate. Some of the above instruments, for example some of the radars, may already be present at the launch sites. An interesting possibility is whether or not the airborne MW radiometer could be adapted to work in a forward pointing mode, thus providing some sort of on board remote icing sensing capability to a UAV.

7. NEEDS AND REQUIREMENTS

As indicated above the useful information to have for icing forecasts are the spatial and temporal distribution of SLW, temperature and humidity profiles and trends, droplet size information, ice/liquid phase distinction, horizontal wind field and convergence, horizontal and vertical vapor flux. The broader needs and requirements, though, revolve around an improved interaction between researchers and designer/operators. UAV systems designers need to understand operational constraints imposed by icing conditions and what technology exists to help them minimize this problem. Researchers need guidance from the UAV users on their priorities and the unique features of UAV systems and missions. The research community can provide the forecasting, sensors and algorithms, while the users can provide the vehicle characteristics and mission profiles. This reciprocal awareness is highly desirable for the success of operational UAV systems. The guiding factors that will figure in the tradeoff studies of icing protection required will be a desired "all weather" capability for UAVs, the importance of mission success, payload constraints, the absence of a pilot, communications constraints, and limitations on personnel and resources.

8. CONCLUSIONS

Aircraft icing is a definite hazard for UAVs, limiting their performance in ways that depend critically on the specific UAV and mission profile. There is a definite need to improve conventional forecasting and instrumentation to maximize the probability of mission success. Recent advances in cloud physics understanding and instrumentation offer hope that such improvement is at hand. Tradeoff studies on the level of icing protection required must include details of the specific UAV and mission.

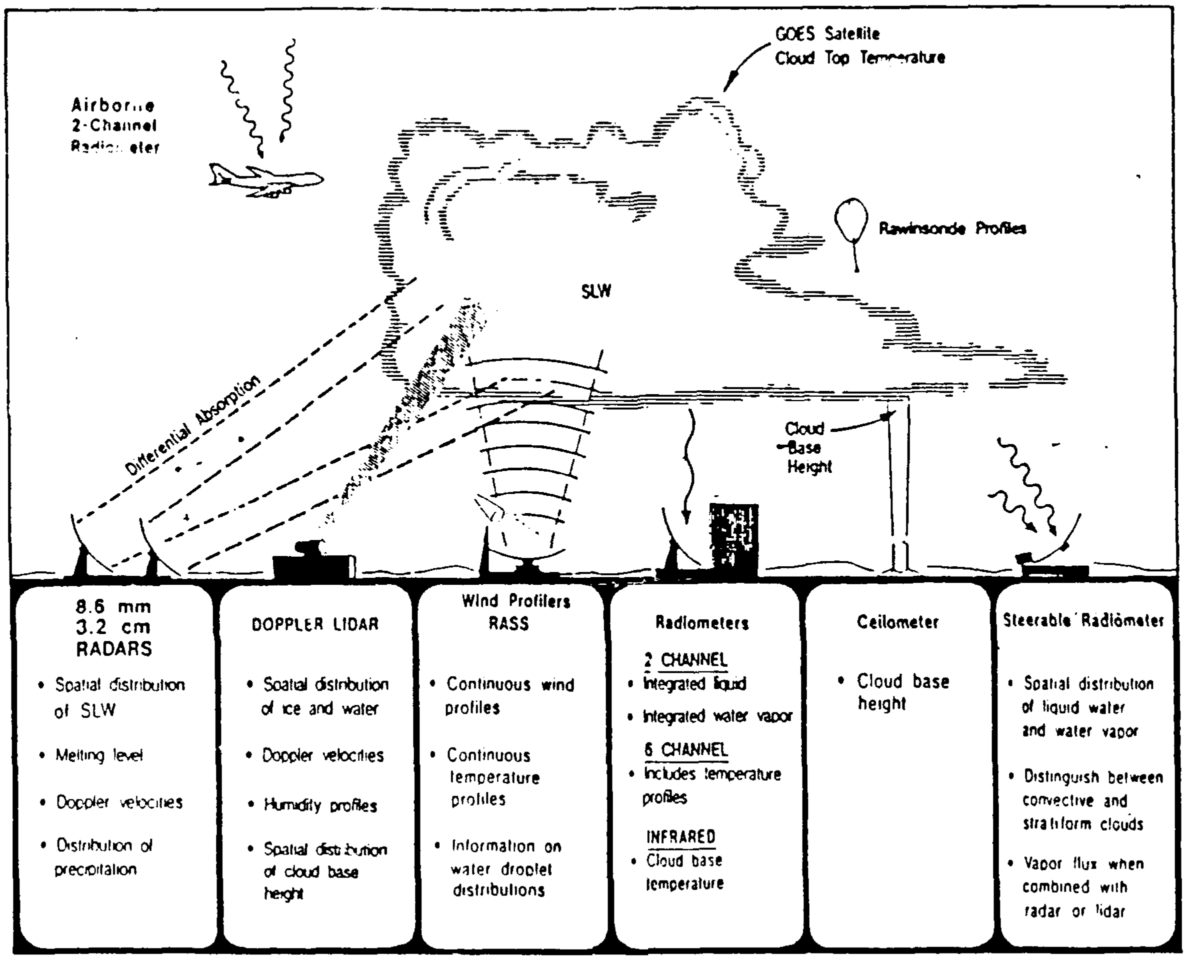

Figure 3. Remote sensing of icing conditions (from Westwater and Kropfli, 1989).

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