P4.5 AN IN-FLIGHT AIRFRAME ICING NOWCAST FOR USE WITH THE AEROSONDE

J.R. Soddell[1], K. McGuffie[1] and G.J. Holland[2]

[1]University of Technology, Sydney
[2]Aerosonde Ltd, Melbourne

1. INTRODUCTION

The Aerosonde, a robotic unmanned aerial vehicle (UAV), is a new atmospheric observing platform that can provide meteorological information over oceans and remote areas, and from within severe weather events such as tropical cyclones Holland *et al.* (2001). Over recent years, Aerosonde missions have been undertaken in varying atmospheric conditions. These include missions in the polar regions, mid-latitudes and the tropics.

Often, aircraft are required to operate in environmental conditions where the probability of aircraft structural icing is high. A large number of aircraft, including the Aerosonde, are currently not fitted with appropriate de-icing equipment to fly safely in known icing conditions. The need for an Aerosonde in-flight airframe icing nowcast became obvious after the loss of two Aerosonde aircraft in 1999, due to structural airframe icing, during operations in the harsh environmental conditions of Barrow, Alaska. As the Aerosonde is a small aircraft even small amounts of ice accumulation may be extremely detrimental to the aircraft. Development of an Aerosonde in-flight icing model began soon after the Barrow incident.

Unlike other icing detection and characterisation schemes developed for full-size aircraft, which have the ability to access and utilise a wide range of operational parameters (e.g. Melody *et al.* (2000)), any scheme for a small aircraft, such as the Aerosonde, must concentrate on information already available and utilise the limited onboard computer resources.

2. THE AEROSONDE ICING DETECTION SCHEME

This Robotic Aircraft Icing Detection (RAID) scheme will provide a useful tool to Aerosonde controllers - by warning of potentially dangerous icing conditions for Aerosonde. It should be noted that this icing scheme does not address the problem of carburettor icing, only providing information on atmospheric conditions that have the potential to cause the accumulation of ice on the surface of an aircraft. To improve the efficiency of the basic RAID scheme, a cloud determination scheme similar to that developed by Chernykh and Eskridge (1996), has also been applied. The RAID algorithm, designed for use during Aerosonde operations, is a simple scheme that relies solely on temperature (T) and relative humidity (RH) observations, collected whilst the Aerosonde is in flight. The overall aim of this in-flight icing scheme is to provide information that can be used to identify possible regions of icing. Once potential icing layers are detected, appropriate measures can be taken during an Aerosonde mission to avoid the potentially hazardous icing areas.

The scheme developed here designates the temperature and relative humidity observations that fell between certain thresholds into three categories (these categories are discussed in further detail below). The current RAID model still incorporates several of the temperature and humidity thresholds, used in various other mesoscale T-RH icing schemes, such as those discussed by Thompson *et al.* (1997).

a. RAID Category 1

The simplest implementation of the RAID algorithm considers regions where temperatures range from 4°C to -40°C, and relative humidity greater than 63%. The upper temperature threshold is based on wind tunnel experiments, where ice accumulated on the surface of a stationary object at 4°C (Lankford, 2000). The lower limit of -40°C is where temperatures become so cold water freezes instantaneously. Therefore, water droplets are unlikely to freeze to the surface of an aircraft at temperatures below -40°C. The relative humidity threshold (63%) is identical to that used in the Research Applications Program (RAP) general icing category. As icing generally occurs in clouds, to reduce the over-estimation of potential icing conditions, the second derivative of each of the temperature (T'') and relative humidity (RH'') data points is then determined. Thus, where the data fits the above thresholds and $T'' \geq 0$ and $RH'' \leq 0$ (Chernykh and Eskridge 1996), the surrounding atmosphere is considered to have potential icing conditions.

Similar to many potential icing forecasts (e.g. the RAP icing algorithm general category discussed by Thompson *et al.* (1997)), this RAID first category generally over-forecasts regions of potential icing. The likelihood of severe icing in these regions is low, however, intermittent icing may still occur.

b. RAID Category 2

The temperature range for this category is reduced in comparison to Category 1. Category 2 thresholds were taken from the research flights into aircraft icing discussed in Sand *et al*. (1984). In-flight icing occurred during the flights examined by Sand et al. (1984) in temperatures between 0°C and -30°C. The relative humidity threshold is set at greater than 75%. The same threshold used in the NAWAU icing scheme, for conditions of category 2 icing conditions (moderate to severe) above the boundary layer (>900m AGL)

---

[1]Address for Correspondence: Jade Soddell
Department of Applied Physics,
University of Technology, Sydney,
PO Box 123, Broadway,
NSW AUSTRALIA 2007
Jade.R.Soddell@uts.edu.au

(Thompson *et al.* 1997). Again, only the observations that fit the Category 2 thresholds, and where $T'' \geq 0$ and $RH'' \leq 0$, are considered to be potential icing conditions.

c. RAID Category 3

This category also requires $T'' \geq 0$ and $RH'' \leq 0$ to be used in conjunction with the thresholds for temperature set as 1°C and -20°C. Lankford (2000) discussed a number of wind tunnel experiments conducted by NASA to determine conditions preferable to the accumulation of structural ice on an aircraft. These indicated that ice will begin to form on an aircraft at 1°C. Between 1°C and -1°C, soft ice is likely to form resulting in a shape of the surface it adheres to. When temperatures drop below -1°C, the ice will harden and become more permanent (Lankford, 2000). Above -20°C, and below 1°C, moderate to severe clear and mixed icing can occur in regions of high relative humidity. Regions fitting this temperature range, and relative humidity values greater than 80%, are highlighted. These regions have a high possibility of icing conditions that could be extremely detrimental to an aircraft in-flight. Moderate to severe icing can result in an ice accumulation rate of greater than 2cm in only one minute (Lankford, 2000). An aircraft the size and weight of the Aerosonde, particularly without de-icing equipment, could find it impossible to recover from these situations.

3. FLIGHT OPERATIONS

During August 2000, 20 Aerosonde missions were undertaken in Barrow, Alaska (71.3°N, 156.7°W). These missions were an integral part of a five year University of Colorado project to measure the atmosphere and sea ice surface in the Arctic Ocean. These flights were the first opportunity to test icing sensors and anti-icing wing coatings on the Aerosonde. The Aerosonde is fitted with two Vaisala RSS901 instruments. Meteorological observations collected by the Aerosonde included pressures, temperature, relative humidity and winds.

4. AEROSONDE OBSERVATIONS (19 AUGUST 2000)

Although not every flight encountered icing conditions during these missions, there were some indications of regions of moderate icing conditions where some loss of engine power was noted. During the 3 hour mission on August 19 (where only a small loss of engine power was recorded by the Aerosonde controller) the piezoelectric icing sensor fitted to the aircraft indicated icing a number of times during the flight, with three very distinct icing episodes (Figure 1). There were 4 instances where the icing sensor failed due to heavy ice accumulation on the leading edges of the aircraft. This was where the icing sensor frequency was observed as at 0Hz. The longest period of flight in icing conditions lasted approximately 22 minutes (21:55-22:16 UTC).

Temperature and relative humidity observations obtained during the times the icing sensor observed icing were between -4.35°C and 1.35°C, and 96.1% and 100%. As the Vaisala instrumentation is unable to accurately measure humidity values in extremely moist conditions (>95%), any relative humidity reading greater than 95% can be considered to be at 100%. There were two periods when the icing sensor observed icing in temperatures above 0°C (between 0.05°C & 0.7°C for the first period and between 1.2°C & 1.35°C for the second).

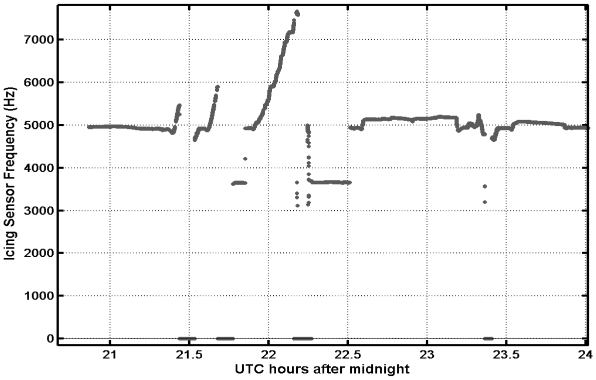

Figure 1. Time series of frequencies recorded by the icing sensor during the August 19, 2000 flight. Icing is present where the measurements progressively increase in frequency, or fall to 0Hz.

TIme series of regions of potential icing conditions predicted by the RAID algorithm (both with and without the incorporation of the cloud scheme), as well as regions of icing recorded by the piezoelectric icing sensor are shown in (Figure 2). A distinct icing layer can be seen between approximately 955hPa-910hPa (in the earlier stages of the flight). The Aerosonde spent a total flight time of approximately 40 minutes at ~910hPa. The icing sensor recorded icing at this pressure level, but later in the flight (~23:54UTC), the level of the icing layer began to gain altitude (900-885hPa). As the atmosphere began to warm slightly. The modelled RAID results and icing sensor data are shown in Figure 3. Where Category 3 icing conditions are present, the greater the potential for more dangerous flight conditions. The aircraft was instructed to descend to a lower atmospheric layer (where conditions allowed the ice to melt off) when ice accumulation became apparent.

5. PERFORMANCE OF THE RAID SCHEME

To obtain more accurate prediction of potential icing areas, the aim is to predict icing conditions accurately while reducing the extent of the regions of potential icing. Over-prediction can lead to less attention paid to regions where extremely hazardous icing may occur. If used for an automated flight response, over-prediction would decrease the effectiveness if aerosonde missions. The initial Aerosonde icing conditions prediction model did not incorporate the cloud determination scheme. To improve on the initial icing scheme (as icing usually only occurs in regions of cloud) the separate identification of regions of cloud was assimilated into the latest version of this model in an effort to reduce over prediction of potential icing conditions.

Overall, with this data set, there was an approximate 63% decrease in the number of observations that fitted the icing scheme parameters when the cloud identification scheme was used in conjunction with the Category 1 icing conditions identification thresholds. When the icing scheme for Category 1 does not also

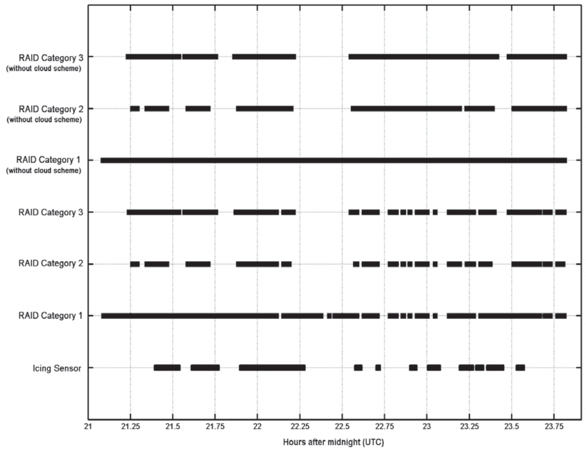

Figure 2. Time series of recorded regions of icing from the icing sensor and regions of potential icing conditions as predicted by the RAID algorithm (August 19, 2000). Model runs both incorporating and without the cloud scheme are shown.

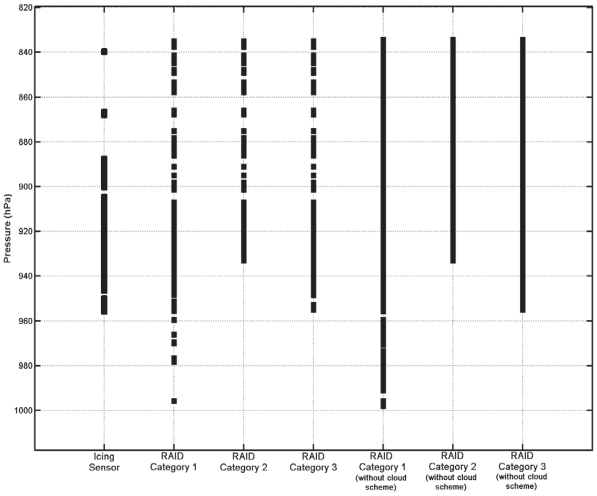

Figure 3. Detected icing and RAID algorithm categories as a function of atmospheric pressure for the August 19, 2000 Aerosonde missions in Barrow, Alaska.

include the cloud identification scheme, almost all the Aerosonde observations fall under the category of potential icing conditions. For the observations that fell in category 2 of the icing scheme, there is approximately a 38% decrease in the number of observations that fall into this category when the cloud scheme is incorporated. For Category 3 (conditions most likely to cause icing) the number of observations indicating icing conditions was reduced by about 45% when the cloud scheme was applied. Thus, an Aerosonde operator will be more informed to judge how harmful current atmospheric environmental conditions are for the aircraft. However, the cloud scheme does not always accurately determine the presence of cloud. The Aerosonde often flies in and out of cloud rapidly. This is unlike a radiosonde that moves vertically through the atmosphere (usually perpendicular to the cloud boundaries), and can spend prolonged periods in marginal cloud areas. When comparing the modelled icing results to the icing observations from the icing sensor there is a large amount of overprediction, as well as underprediction of potential icing conditions. Forty-five percent of the icing locations identified by the icing sensor were accurately identified by the Category 1 icing prediction algorithm. Thirty-two percent and 44% of the icing sensor observations were correctly identified by the Category 2 and 3 algorithms, respectively. Only 50% (Category 1), 48% (Category 2) and 44% (Category 3) of the modelled data accurately predicted icing conditions.

When applying the icing scheme using only the temperature and relative humidity thresholds without the cloud scheme, there is an improvement in the overall percentage of icing observations accurately predicted by each category (Figure 3). However, the number of predicted regions of icing that are *not* observed by the icing sensor also increases. Although the underprediction of regions of icing has decreased, there is an increase in overprediction. When applying the icing algorithms without incorporating the cloud scheme, the percentage of regions of icing observed by the sensor correctly identified by the icing model increases dramatically (e.g. 100% (Category 1), 72% (Category 2) and 90% (Category 3)). However, only 30% (Category 1), 37% (Category 2) and 38% (Category 3) of the predicted regions of icing conditions were accurate.

6. DISCUSSION

Analysis of each of the three Categories in the RAID scheme (with and without incorporating the cloud scheme) has shown that the least effective Category for the prediction of icing conditions was Category 2. The maximum temperature threshold for this category was only set at 0°C. Many of the icing periods detected by the sensor observed temperatures above 0°C, with a maximum temperature of 1.3°C. This particular category may be more effective at much lower temperatures (i.e. <-30°C). For future application of the RAID algorithm (with and without the cloud scheme), modification of the temperature and relative humidity thresholds may be beneficial. Increasing the Category 2 maximum temperature threshold from 0°C to 2°C and the minimum threshold from -30°C to -20°C, and decreasing the threshold range for Category 3 from -20°C-1°C to -12°C-(-1°C) may improve the accuracy of predictions and highlight were the potential for airframe icing may be more severe.

Although Category 1 (without incorporation of the cloud scheme) was the most successful in prediction of icing conditions, this category also greatly over-predicted potential regions of icing. As this category predicted that the Aerosonde was flying almost constantly in icing conditions, an Aerosonde controller is less likely to take any nowcast of icing conditions by this category too seriously, and unlikely to alter the Aerosonde flight path and altitude when necessary. Therefore, even though the addition of the cloud scheme to the icing algorithms may not always predict regions of icing, over prediction is reduced. Category 3 (incorporating the cloud scheme) generally performed well when the Aerosonde maintained a constant altitude/pressure (e.g. when icing was observed by the sensor when the aircraft was maintaining a constant pressure of ~910hPa). Further research, including icing missions with the icing sensor fitted to the Aerosonde, will allow further development and improvement of the Aerosonde icing nowcast.

7. ACKNOWLEDGEMENTS

This research is funded in part by the Australian Research Council through the Australian Postgraduate Award (Industry) Scheme with the Bureau of Meteorology SSU and Aerosonde Ltd. The authors would like to thank all the Aerosonde Ltd staff involved in the Barrow Missions. Many thanks to Jon Becker, Greg Tyrell and Maurice Gonella for their knowledge and support.

8. REFERENCES

Chernykh, I. V. and R. E. Eskridge, 1996: Determination of cloud amount and level from radiosonde soundings. *Journal of Applied Meteorology,* 35, 1362-1369.

Holland, G. J., P. J. Webster, J. Curry, G. Tyrrell, D. Gauntlet, G. Brett, J. Becker, R. Hoag, and B. Vaglienti, 2001: The Aerosonde robotic aircraft: A new paradigm for environmental observations. *Bulletin of the American Meteorological Society*, 889-901.

Lankford, T. T., 2000: *Aircraft Icing: A pilot's guide to supercooled drizzle droplets, icing accident case studies and cold weather techniques.* Practical Flying Series, McGraw-Hill Companies, Inc., pp.336.

Melody, J. W., T. Basar, W. R. Perkins, and P. G. Voulgaris, 2000: Parameter identification for inflight detection and characterization of aircraft icing. *Control Engineering Practice*, 8, 985-1001.

Sand, W. R., W. A. Cooper, M. K. Politovich, and D. L. Veal, 1984: Icing conditions encountered by a research aircraft. *Journal of Climate and Applied Meteorology*, 23, 1427-1440.

Thompson, G., R. T. Bruintjes, B. G. Brown, and F. Hage, 1997: Intercomparison of in-flight icing algorithms - Part I - WISP94 real-time icing prediction and evaluation program. *Weather & Forecasting*, 12, 878-889.