Detection of High Ice Water Content Conditions:
Status of Nowcasting Tool Development for Avoidance of Ice Crystal Icing Events

J. Haggerty, A. Rugg, G. McCabe, C. Kessinger
National Center for Atmospheric Research, Boulder, Colorado

J. W. Strapp (MetAnalytics, Toronto, Canada)

R. Potts (Bureau of Meteorology, Melbourne, Australia)

R. Palikonda (SSAI, Hampton, Virginia)
High Ice Water Content (HIWC) Conditions: Significance to Aviation Operations

- Large concentrations of small ice crystals can exist in areas of convective clouds with low radar reflectivity
- Ice crystals stick to warm metal surfaces in jet engines
  - Ice accretes; accumulated ice can block flow into engine core or shed into compressor
  - Result may be power surge, power loss, engine damage
- Aircraft data systems may also be affected by ingest of ice crystals into inlets
  - Result may be errors in temperature, air speed, and angle of attack

Over 150 Ice Crystal Icing events confirmed to date
(Event locations provided by M. Bravin, Boeing, 2015)
Detect HIWC Conditions

Operationally available data

Blend via algorithms using fuzzy logic and hard thresholds

Gridded field of HIWC potential

The Algorithm for Prediction of HIWC Areas (ALPHA)

- **Satellite**
  - Find highest, coldest, thickest clouds from Total Water Path, Cloud Top Height, and Cloud Top Temperature
  - Total Satellite Interest

- **Model**
  - Find deep cloud layer, heavy precipitation, high condensate, updrafts, temperature below -15°C
  - Total Model Interest

- **3D Radar Mosaic**
  - Find active updrafts, high reflectivity in column along with heights of 10 and 30 dBz echo tops
  - Total Radar Interest

**Calculate Total HIWC Interest**

Weighted Combination of Satellite, Model, and Radar Interest

= Total HIWC Interest
Regional Implementations of ALPHA v1.0 in Support of HIWC Field Experiments

Darwin
- ACCESS model, MTSat, BOM ground based radar
- 2014 field campaign; now running in “playback” mode for data analysis

Cayenne
- WRF model, GOES, MSG
- 2015 field campaign; now running in “playback” mode for data analysis

CONUS
- WRF model, GOES, NEXRAD
- Real-time operation
- Experimental products shared with select users

Florida
- WRF model, GOES, NEXRAD
- 2015 field campaign
Data Set Used for Objective Re-Design of ALPHA

- Three field campaigns
  - 23 flights around Darwin, Australia
  - 16 flights around Cayenne, French Guiana
  - 10 flights around Ft. Lauderdale, FL

- IWC Measurements
  - In situ Isokinetic Probe
  - Cloud radar retrievals of IWC profiles

- Observed IWC values up to \( \sim 4 \) g/m\(^3\)
Input Variables vs. Observations of IWC

- 24 radar, satellite, and model fields evaluated for relationship to HIWC potential
- Histogram shows single variable vs. fraction of airborne observations with moderate or greater ice water content (IWC)
- Blue (green) bars indicate the fraction of observations where IWC exceeded 0.5 g/m³ (1.0 g/m³)
- Variables showing best correlation to IWC measurements retained in ALPHA
Machine Learning for Objective Algorithm Design

Particle Swarm Optimization (PSO)

- Iterative, stochastic, supervised machine learning technique for objective algorithm development
- “Particle” positions represent the set of fuzzy logic parameters needed for ALPHA
- After multiple iterations, particles arrive at sets of parameters that best reflect the in situ IWC data

Application to ALPHA

- Fuzzy logic approach allows for multiple degrees of freedom including:
  - definition of input variable set
  - form of membership functions
  - weighting factors to blend data
- Training data set from flight level IWC measurements
  - 2/3 of flights for training; 1/3 reserved for verification
- Pearson’s correlation parameter used as performance metric for PSO
### ALPHA v2.1

**Membership Functions and Weighting Factors**
generated by Particle Swarm Optimization

![Graph of BTD (6.8μm - 10.8μm) Satellite Weight: 16.0%](image)

<table>
<thead>
<tr>
<th>Product</th>
<th>Satellite</th>
<th>Radar</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Input Day</td>
<td>0.889</td>
<td></td>
<td>0.111</td>
</tr>
<tr>
<td>2-Input Night</td>
<td>1.000</td>
<td></td>
<td>0.000</td>
</tr>
<tr>
<td>3-Input Day</td>
<td>0.710</td>
<td>0.290</td>
<td>0.000</td>
</tr>
<tr>
<td>3-Input Night</td>
<td>0.256</td>
<td>0.449</td>
<td>0.295</td>
</tr>
</tbody>
</table>
Verification with Reserved In Situ Data
Probability of Detection vs. False Alarm Rate

ALPHA 2.1 Comparison: Verification Data

ALPHA 2.1 By Location: All Data

Version 2.1
Version 2.0
Version 1.0

Darwin
Cayenne
Florida
Verification with Reserved In Situ data – Probability of Detection

**PoD-yes:** 77.3%

**PoD-no:** 79.4%

**Misses:** 22.7%

**False Alarm Rate:** 20.6%
Summary

• ALPHA is a diagnostic product for estimating the potential for HIWC conditions
• Analysis of airborne measurements has enabled us to objectively optimize the algorithm
  – ALPHA fuzzy logic-based algorithms “trained” to simulate airborne IWC observations from three field campaigns
  – New membership functions and weighting factors determined for satellite, model, and radar input variables
  – Probability of detection statistics improved compared to ALPHA v1.0

Future Work

• ALPHA v2.1 product
  – Regional tuning and additional validation

• Compile frequency and duration statistics of HIWC features

• Explore operational applications
  – Experimental CONUS and Australian products
Questions?

This research is in response to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA.
## Data Sources for HIWC Detection

<table>
<thead>
<tr>
<th></th>
<th>Satellite (vis/IR)</th>
<th>NWP Model (operational)</th>
<th>Radar (ground based)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td>Global Availability</td>
<td>Global Availability</td>
<td>High spatial resolution</td>
</tr>
<tr>
<td></td>
<td>Moderate spatial resolution</td>
<td>3-Dimensional Forecasting capability</td>
<td>3-Dimensional</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>2-Dimensional (cloud top)</td>
<td>Limited ability to capture convective processes</td>
<td>Regional availability</td>
</tr>
</tbody>
</table>

**Satellite**
- Global Availability
- Moderate spatial resolution

**NWP Model**
- Global Availability
- 3-Dimensional Forecasting capability

**Radar**
- High spatial resolution
- 3-Dimensional
- Regional availability
## Input Variables Considered for Use in ALPHA

<table>
<thead>
<tr>
<th>Satellite</th>
<th>NWP Model</th>
<th>Groundbased Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Cloud Top Temperature</td>
<td>Temperature</td>
<td>Maximum Reflectivity in Column</td>
</tr>
<tr>
<td>Effective Cloud Top Height</td>
<td>Surface Precipitation</td>
<td>Maximum Height of 30 dBz Reflectivity</td>
</tr>
<tr>
<td>Total Water Path</td>
<td>Total Condensate</td>
<td>Maximum Height of 10 dBz Reflectivity</td>
</tr>
<tr>
<td>Optical Depth</td>
<td>Total Water Path</td>
<td>Vertically Integrated Liquid</td>
</tr>
<tr>
<td>Brightness Temperature Difference (6.7 – 10.8 um)</td>
<td>Vertical Velocity</td>
<td>Volume Averaged Height Integrated Reflectivity</td>
</tr>
<tr>
<td>Brightness Temperature Difference (10.8 -12 um)</td>
<td>Tropopause Height</td>
<td>Precipitation Ice Mass</td>
</tr>
<tr>
<td>Convective Available Potential Energy, Convective Inhibition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Divergence/Convergence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vorticity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>