Development of Simulation and Evaluation for High Ice Water Content (HIWC) Hazard Detection Using Airborne Radar

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ABSTRACT

High Ice Water Content (HIWC) is an atmospheric condition at high altitude that may lead to failure of jet engines. As a potential threat to aviation safety and space launch operation, it has received significant attention from cross-disciplinary communities. Detecting HIWC conditions with airborne radar is essential to the safe monitoring of this type of hazard, however it has unique and significant challenges. For example, in general, clusters of small ice particles do not register strong radar reflectivity, which is a challenge to the sensitivities and resolutions of small aperture airborne radars. Second, it is difficult to discriminate HIWC from other atmosphere conditions, such as general precipitation, and evaluate the threat level (in quantity of Ice Water Content, or IWC) with remote sensing only. In this study, we developed a novel simulation-based approach, which uses the in-situ cloud probe data collected in HIWCs during a series of flight test campaigns, as well as the microphysical particle models retrieved from these data. Then, we combine and reconcile these models with ground-radar measurements, which leads to a three-dimensional truth gird. Using this truth field, we developed a single-cell-Monte-Carlo (SCMC) simulation implementation, which creates and generates airborne weather radar signatures and moments for each individual resolution cell. The simulation has incorporated (1) An initial framework of airborne radar system and sensor modeling, (2) Modeling of ground clutter and the effect of antenna patterns. The simulation tool has significant applications in the areas of (1) Guidance of designing developing the next generation airborne hazard sensing and avoidance radars. (2) Support of industry standard making and performance evaluations such as done by the FAA, and (3) Support of scientific studies on airborne radar signatures and techniques for further understanding of hazardous atmosphere conditions for aviation.

Keywords: HIWC, Aviation Hazards, Airborne Radar, Sensitivity

1. INTRODUCTION AND MOTIVATION

High clouds with High Ice Water Content (HIWC) represent a significant aeronautical hazard and a threat to jet engine operations at high altitudes[1–5] including commercial transportation vehicles, rockets, super-sonic vehicles and other space exploration mission platforms. International studies, flight campaigns, and modeling studies have been ongoing to address the HIWC challenge.[6] Currently, scientific teams at NASA, OU and elsewhere are working towards better understanding the microphysical processes causing HIWC at high altitudes. Despite the research progress, there are still significant gaps between current research and the operational needs of NASA and industry. The active FAA-RTCA working group[7] on HIWC detection has been seeking to develop the minimum operational performance standards for HIWC detection for commercial airborne weather radars. There are critical and fundamental questions that need to be answered within an urgent schedule, such as the criteria for declaring the hazards, the detection ranges, and validation of radar capabilities. In terms of testing

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and evaluation, past flight campaigns were mainly limited to the collection of in-situ measurements and some collocated radar measurements. There is also a strong need to incorporate dual-polarization capability into the airborne radar sensor, since polarimetric radar observations are critical for better characterizing microphysical properties of clouds.[8–10] Radar polarimetry offers one of the most promising solutions for HIWC identification and quantification[8,10,11]

Since the need of new sensing capabilities are being contemplated, and the actual flight test data collection is still limited, simulation is considered as an important tool for the radar manufacturers to evaluate the system performance at initial stage and reduce risks on the sensor developments. As an example, the proposed "Swerling" algorithm[12] relies on the pulse-to-pulse variance of the radar receive power that is caused by the ice particles in the resolution volume. Even though this method is largely validated through flight test data, simulations would provide better understanding of the underlying physical process. Unfortunately, the current airborne weather simulations tools[13] are not sufficient due to the following reasons: (1) The "truth data", which usually come from Numeric Weather Prediction (NWP) model data, may not contain enough physical information to model pulse to pulse fluctuations of radar I/Q data. (2) The effects of radar antennas (and other system parameters) have not yet been fully addressed, especially in 3D cases. (3) Computational load is difficult to control. Through the process of developing a new physics-based radar simulation model for HIWC, we realized that tradeoff must be made among the physical modeling accuracy, radar sensor model accuracy, and computational load requirements. We have achieved an initially optimized compromise through simplified microphysical modeling, scalable radar modeling, and modular simulator solutions.

This paper contains two distinct parts. The first part focuses on introducing a physics-based, radar cross-section (RCS) fluctuation model for radar resolution cells containing ice crystal targets, expressed as statistical distribution of reflectivity factor (Z) of a radar resolution volume. The second part focuses on how such target models are incorporated into a MATLAB-based airborne radar system simulator, and validations in conjunction with measured flight test data.

2. OVERALL SIMULATION CONCEPT

The overall system simulation concept is described in Figure 1. In this scheme, the HIWC "target" model and the airborne radar sensor system model are integrated into one completed package. The goal of this package, which combines software pieces written in Fortran, C, MATLAB and Python, is to provide end-to-end evaluations and risk mitigations for airborne weather radar manufacturers.

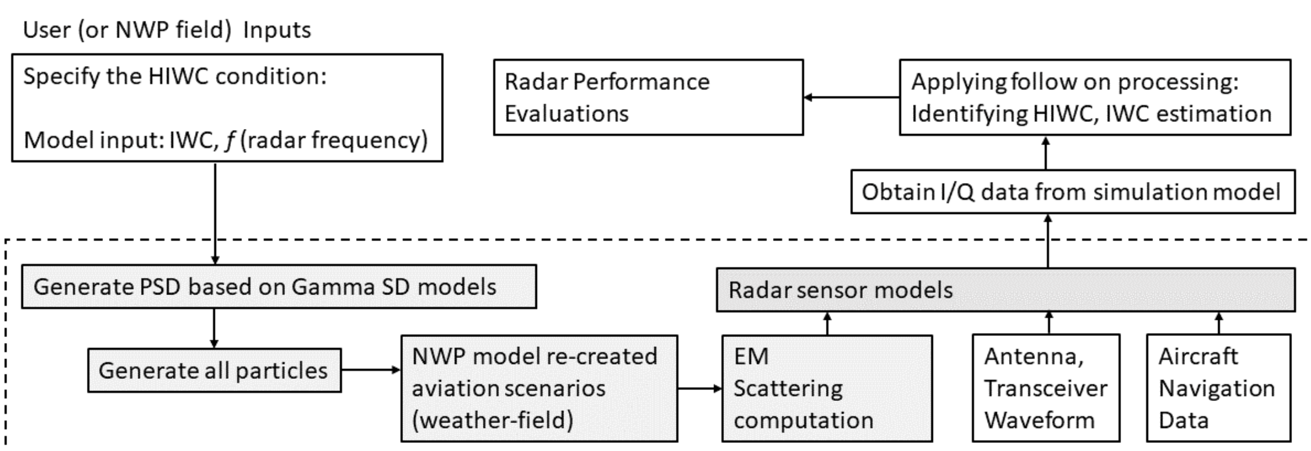


Figure 1. Overall simulation systems, which combines the HIWC target model with the "backend" radar simulators.

3. RADAR TARGET MODEL

From numeric weather prediction (NWP) model outputs, a “cell” refers to a rectangular box from the model output grid, which is usually defined in rectangular coordinates. For unit (1 cubic meter) cell size, for example, the number of ice particles in the cell will be well-characterized by the particle size distribution (PSD). The challenge is how to accurately describe the radar cross section (RCS) per volume and the probability distribution of it. Our approach is taking each single “cell” as shown in Figure 2 as an equivalent point target. The probability distribution function (PDF) of the reflectivity factor values, which is in proportional to the RCS per volume, determines the pulse-to-pulse fluctuations of the equivalent complex RCS.

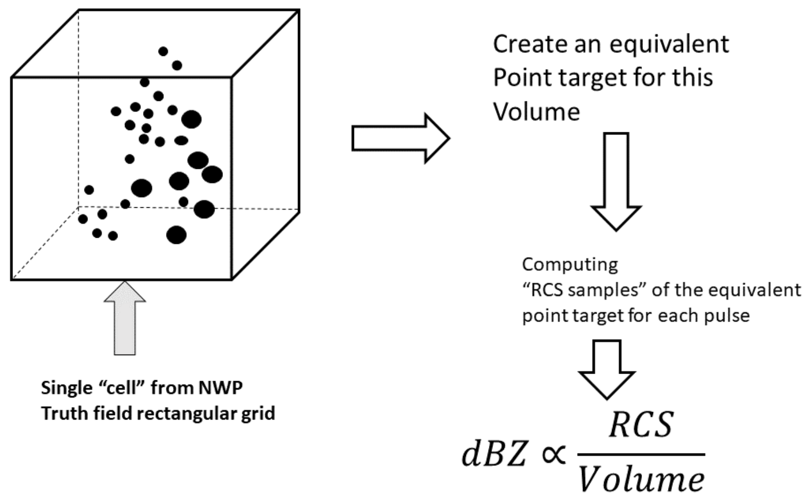


Figure 2. Single cell Monte Carlo (SCMC) method.

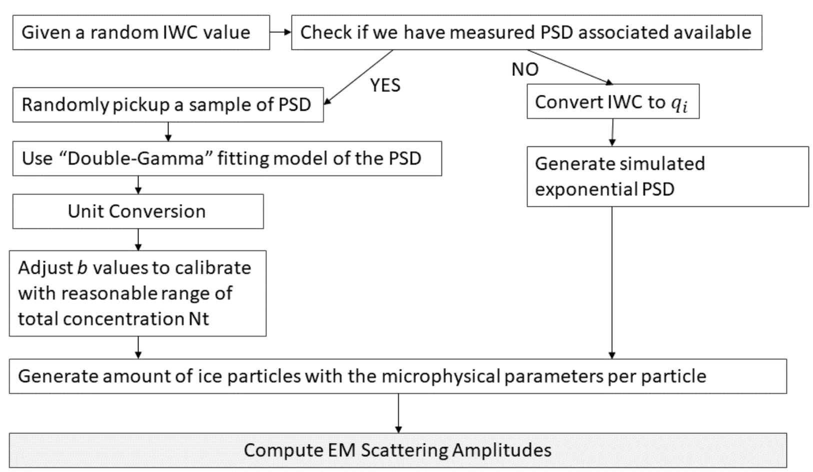


Figure 3. SCMC running flow.

Hence, a “single-cell” Monte-Carlo simulation method is developed based on this modeling. The algorithm and procedure of generating the PDF of reflectivity or complex RCS is depicted in the following Figure 2. The key step of this simulation is invoking appropriate PSDs for a given IWC. If the PSDs are available from previous

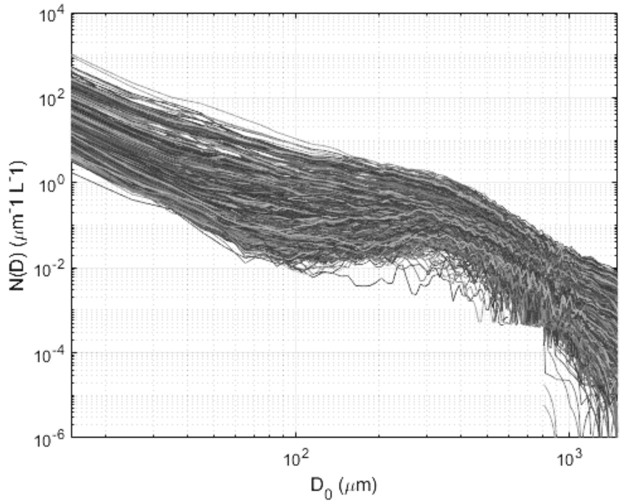


Figure 4. Measured particle size distribution (PSD) using Cloud Droplet Probe (CDP) during a flight campaign.

Table 1. Summary of SCMC model parameters.(* Assuming M-P DSD here. In the latest model, the PSD shape is described by a set of 8 parameters (double-Gamma))

Model Parameter	Physical Meaning	Unit	Allowable Range	User (TASS)/ Internal	Update Interval
N_o	Intercept parameter of DSD	m^{-4}	$10^6 to 10^8$	Internal (from IWC)	Scan
N_t	Total concentration	$\#/m^3$	$10^4 to 10^6$	Internal	Scan
D_m	Mean equivalent volume diameter	mm	0.1 to 1 mm	Internal	Scan
D_e	Volume equivalent diameter	mm	0.1 to 1 mm	Internal	Scan
L	Axis ratio	NA	0.5 to 0.7	Internal	Scan
c, d	Shape parameters	NA	0.01 to 1	Internal	CPI
σ_θ	Canting angle distribution	deg	10 - 20	Internal	Pulse
$\wedge^*$	Slope of DSD	mm	1 to 10	Internal	Scan
α	rho-D relation parameter	g	0.01 to 0.1	Internal	CPI
β	m-D relation parameter, default=-1	NA	NA	Internal	CPI
IWC	Ice water content of the radar resolution volume	g	0.5 to 5	User input	Scan
f	Radar frequency	GHz	X band	User input	Scan
ρ_{ice}	Effective density of ice	g/cm^3	X-band, temperature	Internal	Scan
ϵ_{ice}	Permittivity of ice	F/m	X-band, temperature dependent	Internal	Scan
T	Temperature	C	-50 – 0	TASS	Scan

flight measurements, we use those measured curves as much as possible. If they are not available, we use some assumptions from literatures, and generate "synthetic" PSDs based on the exponential model.

More details of the SCMC internal procedure are shown in Figure 3. The IWC value can be provided by the user of simulator or reading from NWP model output field data. We can randomly pickup a measured PSD from the flight campaign database, which is associated with the IWC value, and use it to populate the particle scatterers within the cell (as shown in Figure 2). Simple calibrations and unit conversions are needed in this step to ensure the total concentration levels are in reasonable and consistent ranges. This selected PSD is fixed for all the Monte-Carlo runs. The next step is generating all the particles within the unit cell (usually in range of 105 to 106) and compute average reflectivity factors from this cell. For each Monte-Carlo run, which corresponds to a sampling of one radar pulse, the relative phases among the particle scattering fields are set randomly between 0 and 2p. In addition, some microphysical parameters are also updated in each Monte-Carlo run, and some other physical parameters are treated as fixed, since they usually do not change during a radar CPI. The summary of these parameters is provided in Table 1. As a result, each SCMC Monte-Carlo run represents the averaged reflectivity (dBz) from this unit cell for given IWC level, and the uncertainty of the reflectivity caused by uncertainty of physical parameters listed in the Table 1, which is manifested as possible fluctuations of dBz values during radar pulse repetition periods.

The source of sample probe-measured PSD is from the following previous flight campaigns: Falcon 20 in Cayenne (French Guiana) during 15:30-19:15 UTC, 23 May 2015, and flight 23 of 2014 Darwin campaign, during the time 22:13:01-22:16:01 UTC. Data from these campaigns have been used in previous HIWC studies. The overlapping plot of the sample PSD data is shown in the following Figure 4, which contains IWC up to 3 g/m3. Usage of measured PSD data allows us to have much better fidelity of the ice crystal PSD than simplified M-P PSD assumptions in some previous studies. Note that these PSD data needs to be fitted and interpolated appropriately, before being used in the SCMC simulation process.

4. SAMPLE SCMC MODEL OUTPUTS AND ANALYSIS

4.1 Histogram and Distribution

The simplest analysis of the SCMC model output is a histogram. For example, we may fix the IWC value and then run a number of Monte-Carlo simulations (such as 5000) and plot the output histograms of reflectivity for each IWC value. Figure 5 shows an example of 5000 Monte-Carlo runs. The distributions from these results show a trend of increasing mean reflectivity in unit of dBz, while showing decreasing standard deviation values, when IWC values increase. However, if we change the value configurations in the SCMC models, the trend may change, and the specific values may be altered. Also, the probabilistic distribution functions extracted from these histograms may not follow Gaussian type of functions.

4.2 Scatterplots

The scatterplots generated from sample SCMC outputs are illustrated in Figure 6. Similar to histograms, they also show general trends of increasing mean reflectivity vs increasing IWC. It also shows increasing "spreading" of the uncertainties of reflectivity vs IWC, which is partially shown in the variance vs IWC distributions.

Comparing to the measurement result data from the previous flight test campaign (2015) as shown in Figure 7, we can see interesting similarity. Further details, however, still need to be investigated. For example, the range of "spreading" of reflectivity dBz values appear to be smaller compared to simulation results. Also, the temperature-dependence of the distribution is more clearly shown in measurement data. In SCMC models, the impacts of temperature are mainly on the ice crystal permittivity, but other impacts may need to be incorporated.

5. HIWC CASES AND SCENARIOS USING SYSTEM SIMULATION

In this section, we use the outputs from Terminal Area Simulation System (TASS), which is one of the numeric weather prediction (NWP) models used by NASA, as the system simulation truth field. TASS data is provided as a part of the NASA HIWC flight program. The dataset was extracted for tropical storms Danny, Darwin, and Knowlton. The data sets consist of several variables like ice water content, radar reflectivity factor, graupel,

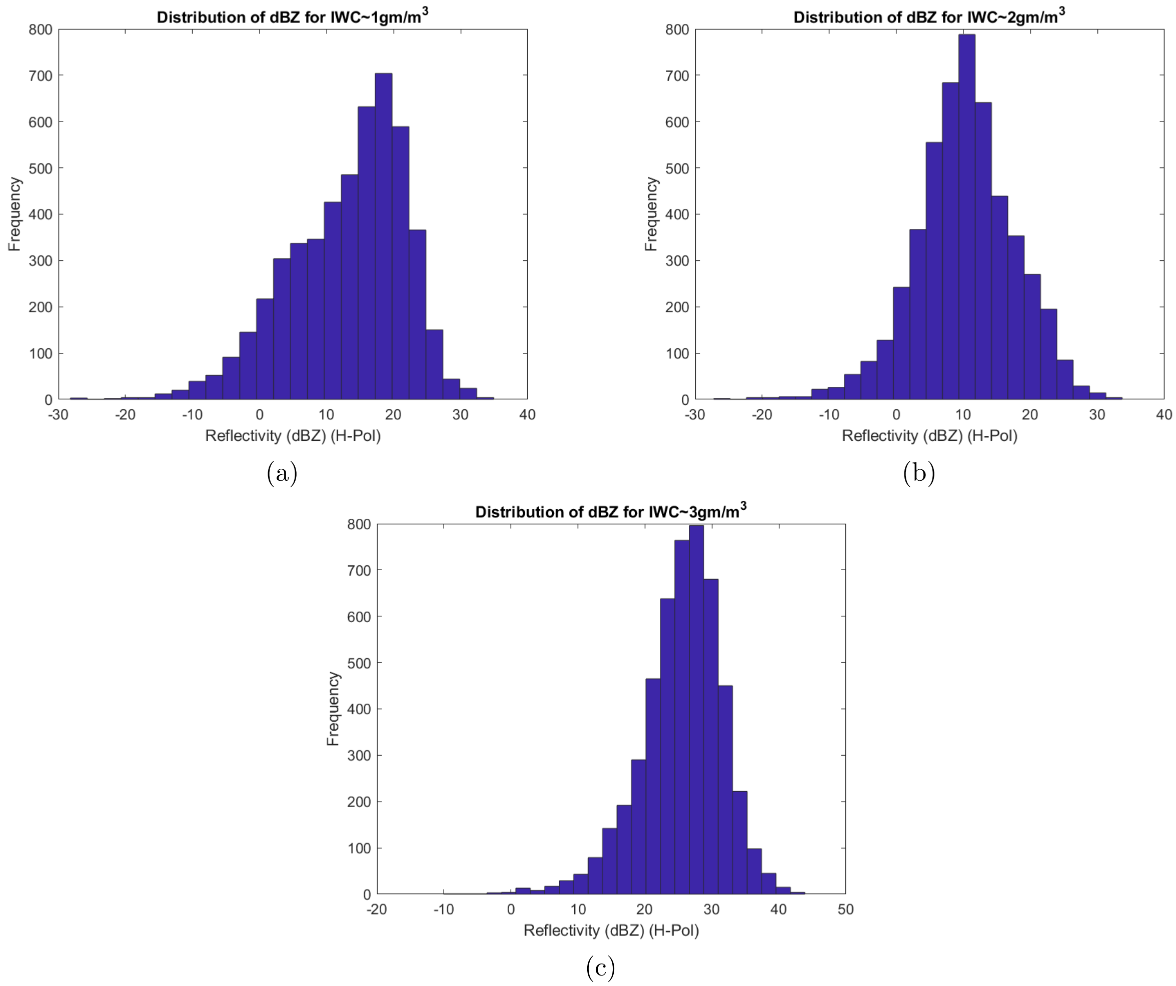


Figure 5. Histogram of Sample SCMC outputs for different IWC levels

wind velocity gridded within three-dimensional Cartesian volumes. Different atmospheric conditions like pressure, temperature, and dew point temperature are also provided and can be useful for radar simulation. In this study, an initial radar simulation based on the TASS data and utilizing MATLAB's phased array toolbox has been performed.

Different variables are provided within three-dimensional Cartesian volumes. For example, in the case of tropical storm Danny, an entire volume of 400km by 400km by 20km is divided into 250m by 250m by 200m individual grids, with meteorological variable values assigned for each grid. The variables like ice water content (IWC) and radar reflectivity (Z) are examples of the individual micro-physical characteristics. As mentioned before, in our current approach, one single point target with RCS fluctuations derived from SCMC is used for each Cartesian grid cell to represent all the individual particles inside the volume.

As an example, a complete radar reflectivity PPI for tropical storm Danny at an altitude of 10.9 km is shown in Figure 8. The two regions with higher IWC, and correspondingly higher reflectivity regions used for the simulation are shown with the assumed location of an aircraft for the radar simulation. The corresponding radar field-of-view (FOV) overlaid on the high IWC region is shown in the Figure 9. Although the most common airborne weather radars have the FOV of 120°, a field of view of 60° has been used to compensate for the computational resources required by the simulation. A summary of the simulation parameters is shown in Table 2. Figure 10(a) and 11(a) shows the nearest neighbor interpolation TASS-Z data for the 60° field of view, and they serve as the references for the qualitative analysis of the simulation results. Figure 10(b) and 11(b) show the

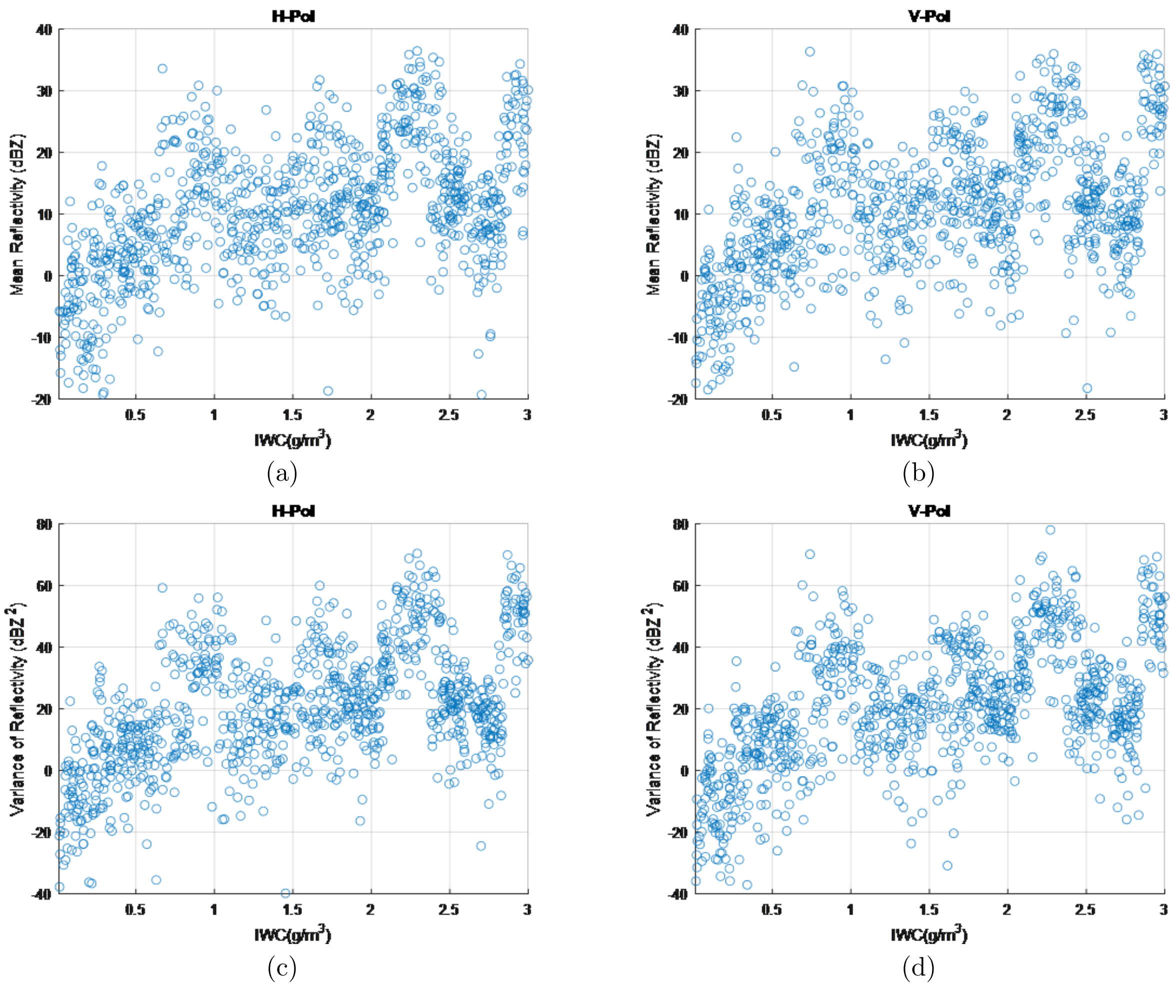
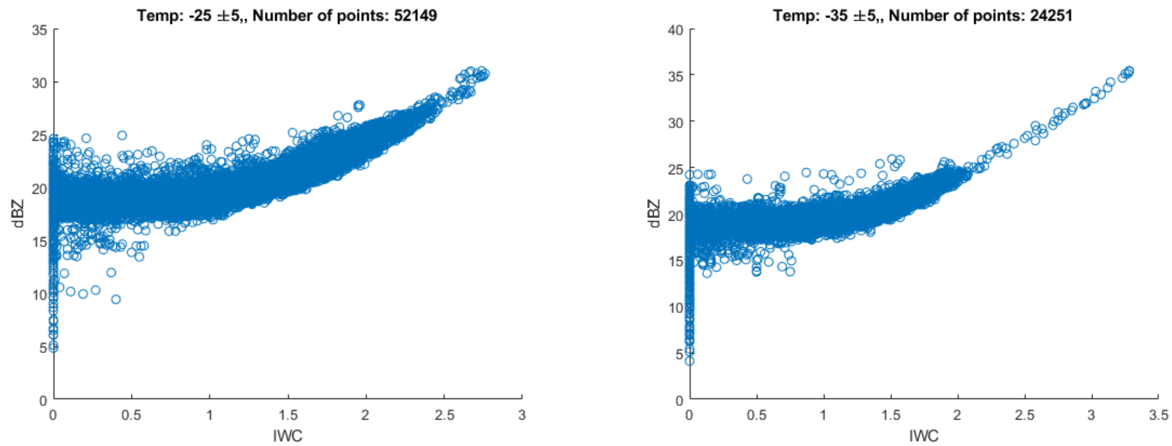


Figure 6. Scatterplots of sample SCMC outputs for different IWC levels. (a) Mean value of reflectivity for 1000 Monte-Carlo runs, H polarization. (b) Mean value of reflectivity for 1000 Monte-Carlo runs, V polarization. (c) Variance value of reflectivity for 1000 Monte-Carlo runs, H polarization, (d) Variance of reflectivity for 1000 Monte-Carlo runs, V polarization.

initial simulation results, for the airborne radar beam (with 6.3 deg beamwidth in both AZ and EL). The regions of high reflectivity are identified in the simulation. There are clear differences between the "truth" 2D fields and the computed PPI scan based on collecting I/Q target returns from 3D fields, and rough pulse-pair estimations using range attenuation correction. The significant differences are likely caused by the 3D field sampling scheme and the 3D antenna pattern effects, as well as relative low SNR (only single pulse return is used). Further investigations are still ongoing and improvements will be reported in the follow-on publications.

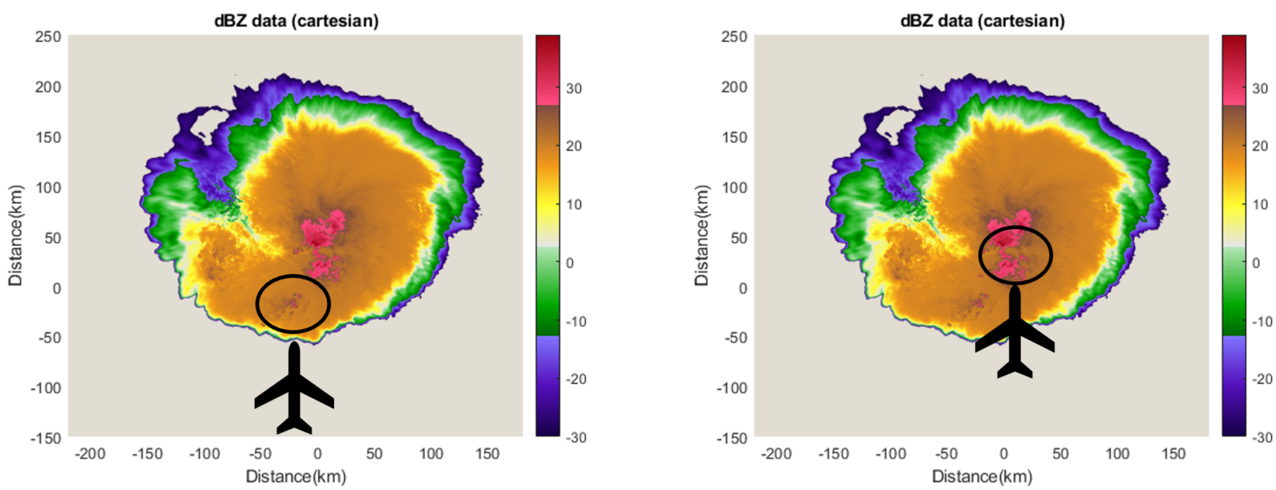
6. INITIAL APPLICATION AND VALIDATION

As it is a significant challenge to estimate IWC levels based on the single-polarized radar measurements, our initial goal is to provide validation of the “Swerling” algorithm developed by NASA-Langley for the HIWC detection and estimation. The basic assumption was that the variations from pulse to pulse in the receive radar signals contain information about the IWC levels. The metric is defined as RIWC (radar estimated IWC, or index of dispersion) as defined in Numrical Solution.[14] The example results based on 1000 Monte-Carlo runs of SCMC are shown in Figure 12. From these preliminary results, it is seen that there is a matching trend between



(a) (b)

Figure 7.
Sample scatterplots of measured airborne radar data from NASA 2015 flight test campaign. The aircraft used was NASA's DC-8. Further details of the flight campaign are discussed in[14]



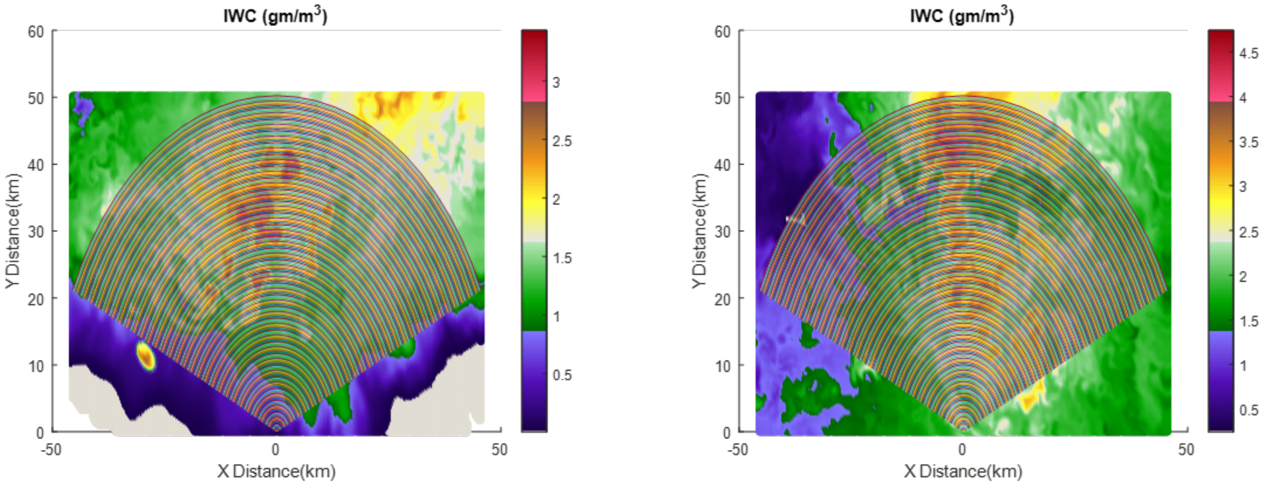
(a) (b)

Figure 8. An entire TASS PPI with Sample region 1 and region 2

the RIWC and truth IWC statistically. However, further validations are necessary, and will be reported in future publications.

7. SUMMARY

The investigations of a "cell-based", microphysical model of HIWC radar return, and its initial applications of airborne weather system simulation is introduced in this paper. Although this new type of hazard has raised tremendous interest internationally, the fundamental physical model and validations with available flight test measurements are still not fully mature. The key innovation of this study is using measured PSD database in the SCMC simulation process. We found that the SCMC concept and the current implementation are able to predict the "basic trends" of the radar signatures with different IWC levels with different polarizations, it also provides preliminary validations of the "Swerling" technique NASA proposed for IWC estimation using single polarized radar. Further, we used the NWP model output as truth fields to analyze the "scenarios", which are mainly based on tropical storm simulations, to perform radar system simulations in MATLAB. Preliminary validation



(a) (b)

Figure 9. Field of View for Sample region 1 and region 2

Table 2. Preliminary Radar Simulation Parameters

Radar Parameters	Values
Antenna Beamwidth	6.3 degrees in both AZ and EL
Frequency	9.4 GHz
Peak Power	360 Watt
Pulse Width	∼20 microseconds
PRF	2998 Hz
Time BW product	∼11.69
Number of Pulses	1 (Single pulse for now, more pulses will be added in later simulations)
Field of View	-30 to 30 degrees (Later simulations will have 120 degrees field of view)

using previous flight campaign data shows promising comparisons, this we believe further investigations on the detailed model parameter setting, incorporation of more measurements, as well as more precise analysis of the IWC estimation based on airborne radar observations are important before the models and simulation systems can be reliably used by the aviation radar industry.

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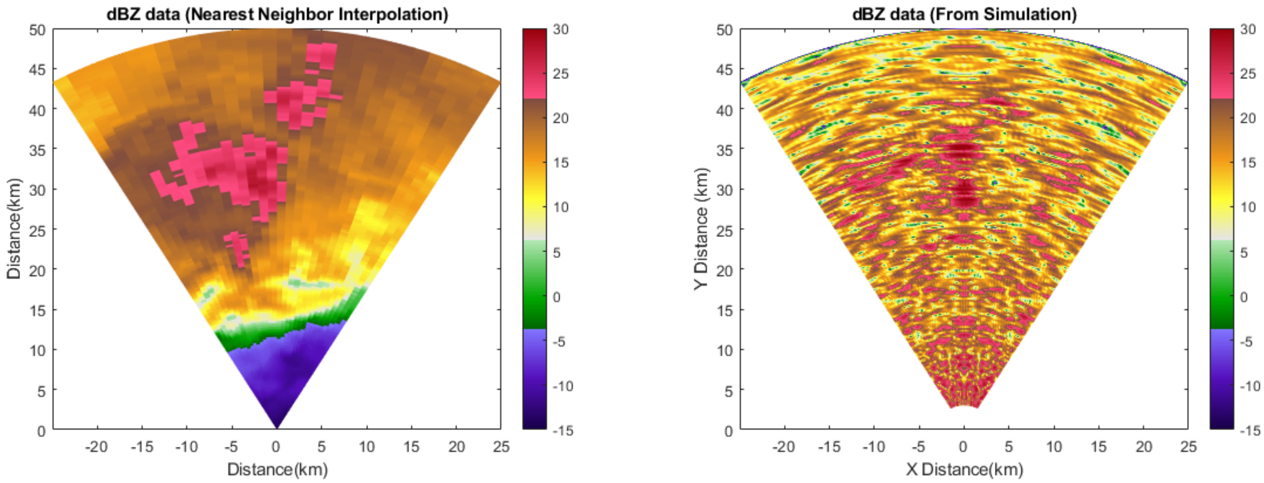
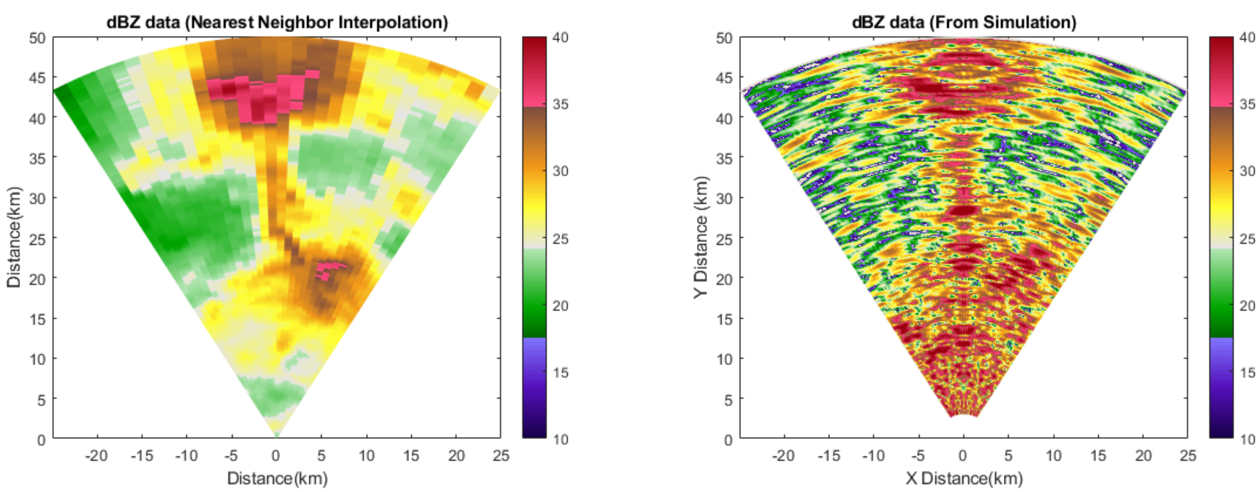


(a) (b)

Figure 10. Comparing ”truth” relectivity data in one 2D plane with current simulated PPI scan from 3D FOV, for sample region 1. (a) 2D reflectivity field read from TASS, (b) simulated 3D airborne radar scan for the FOV



(a) (b)

Figure 11. Comparing ”truth” relectivity data in one 2D plane with current simulated PPI scan from 3D FOV, for sample region 2. (a) 2D reflectivity field read from TASS, (b) simulated 3D airborne radar scan for the FOV

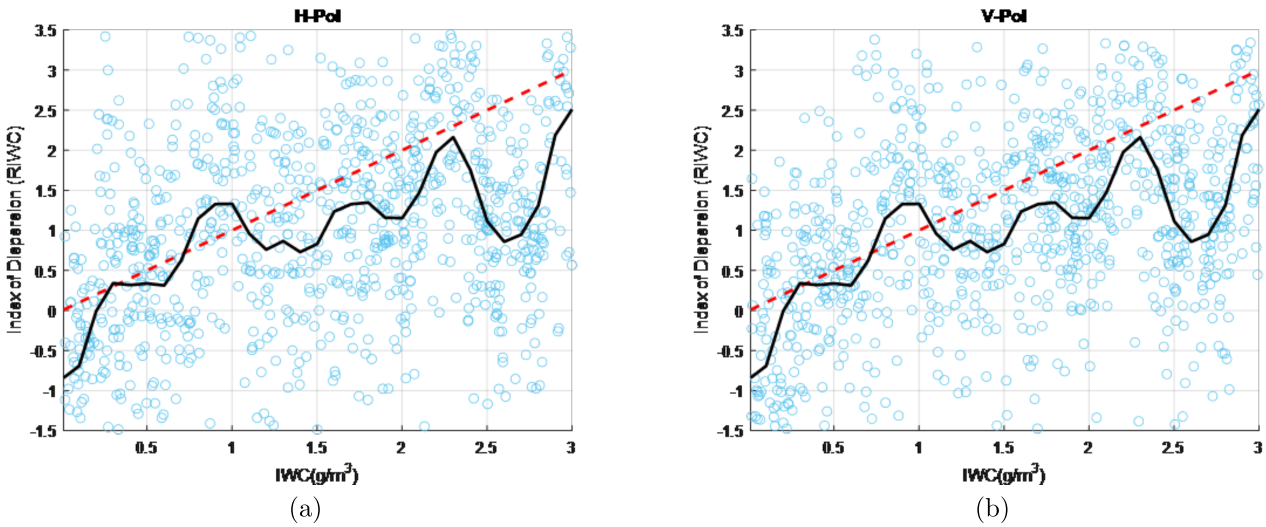


Figure 12. The calculated RIWC (or index of dispersion) values from SCMC simulation runs, based the scatterplots, the solid line is the averaged RIWC values from all simulation runs, and the dashed lines represent the “ideal” linear relation. (a) Results for H-polarization. (b) Results for V-Polarization.

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