Comparing Aircraft Observations of Snowfall to Forecasts Using Single or Two Moment Bulk Water Microphysics Schemes

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High resolution weather forecast models with explicit prediction of hydrometeor type, size distribution, and fall speed may be useful in the development of precipitation retrievals, by providing representative characteristics of frozen hydrometeors. Several single or double-moment microphysics schemes are currently available within the Weather Research and Forecasting (WRF) model, allowing for the prediction of up to three ice species. Each scheme incorporates different assumptions regarding the characteristics of their ice classes, particularly in terms of size distribution, density, and fall speed. In addition to the prediction of hydrometeor content, these schemes must accurately represent the vertical profile of water vapor to account for possible attenuation, along with the size distribution, density, and shape characteristics of ice crystals that are relevant to microwave scattering.

An evaluation of a particular scheme requires the availability of field campaign measurements. The Canadian CloudSat/CALIPSO Validation Project (C3VP) obtained measurements of ice crystal shapes, size distributions, fall speeds, and precipitation during several intensive observation periods. In this study, C3VP observations obtained during the 22 January 2007 synoptic-scale snowfall event are compared against WRF model output, based upon forecasts using four single-moment and two double-moment schemes available as of version 3.1. Schemes are compared against aircraft observations by examining differences in size distribution, density, and content. In addition to direct measurements from aircraft probes, simulated precipitation can also be converted to equivalent, remotely sensed characteristics through the use of the NASA Goddard Satellite Data Simulator Unit. Outputs from high resolution forecasts are compared against radar and satellite observations emphasizing differences in assumed crystal shape and size distribution characteristics.
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Introduction
- High resolution forecasts are produced from double-moment microphysics schemes to simulate the evolution and precipitation of various hydrometeor shapes.
- Model output can be used to generate representative cloud and precipitation fields for use within satellite simulations, assisting in the development of precipitation and cloud property retrievals.
- These schemes include assumptions about particle size distribution, mass-diameter, and diameter-fall-speed relationships, requiring evaluation.

Hydrometeor Profiles
- Ice water content observed onboard the aircraft is a counterflow virtual impactor (CVI; Twomey et al. 1997). Although liquid water measurements were also available, no appreciable liquid water content was reported (Figure 2).
- Conditional mean profiles of hydrometeor content were produced from WRF model profiles within 50 km of the King City radar.
- All schemes generally reproduced the aircraft vertical profiles of ice content, with some place greater emphasis on small cloud ice crystals.
- The dominance of the snow category is supported by CVN and radar observations of ice crystals and aggregates throughout the vertical column.

Water Vapor Profiles
- Mean profiles of water vapor differ substantially among the forecasts and are shown in terms of relative humidity in Figure 3.
- Differences are likely attributable to the saturation adjustment process within each scheme, division or sublimation terms.
- The modal size of aircraft observations reported an environment saturated (supercooled) with respect to water (ice).
- The Thompson scheme performs well until temperatures cool to -10°C, then is affected by the saturation adjustment scheme selected for this simulation.
- The WSM4/WSM5 forecasts produced an environment unsaturated with respect to water throughout the vertical column, but with slight ice supercooling.
- The Thompson and Morrison schemes follow the general trend in observations, while the SCE-Lin forecast smoothly decreases saturation with respect to water at altitudes above 2 km.

Size Distribution Parameters
- Aircraft measurements included imaging probes with crystal imagery used to construct particle size distributions (PSDs) binned by maximum diameter.
- Although the Thompson scheme uses a very specific PSD, remaining schemes use a generalized gamma distribution (1), with dispersion parameter set to zero, resulting in an exponential size distribution.
- Exponential size distributions were fit to each of five aircraft PSDs with parameters retained if the resulting best-fit distribution was well-fit to observations (Figure 4).
- Size distribution parameters were obtained from model output data based upon their assumed PSD characteristics or parameterizations. Resulting variables were converted to mean profiles acquired within 50 km of the King City radar (Figure 4).

Comparing Moments of Size Distributions
- Particle size distributions were also compared by examining their moments. This is particularly valuable for the Thompson scheme, which predicts the second moment of the PSD and infers remaining moments as a function of temperature.
- Relationships in the Thompson scheme are based upon aircraft measurements of ice crystals and temperature-dependent functions between moments.
- The second moment, or $\beta_2$, can be calculated as $M_2 = \frac{\lambda^2}{\lambda}$
- Resulting comparisons between aircraft PSDs and model profiles are shown for select moments in Figure 5.
- Model profiles for the Thompson scheme are based upon temperature-dependent relationships used within the forecast.
- Double moment representation in the Morrison scheme provides a better depiction of aggregation effects. Other vertical trends in aircraft observations are best represented by schemes that provide flexibility in PSD characteristics.

Snow Characteristics in Selected Microphysics Schemes
- Water Vapor
  - Fixed distribution intercept
  - Fixed density spheres
  - WSM4
    - Single moment
    - WSM5
    - Single moment
  - Thompson
    - Single moment
    - Non-spherical mass number relationship
  - Michele
    - Single moment
    - Ice density characteristics range from dry to graupel dielectric constant
    - Distribution intercept a function of temperature
    - Ice density characteristics range from dry to graupel dielectric constant
  - Morrison
    - Double moment in all species
    - Freezing density spheres

Terminal Velocities
- Terminal velocity and diameter relationships combine with PSD and simulated mass content to determine precipitation against scheme assumptions.
- Surface observations of fall speeds were obtained from the Hydrometeor Velocity and Shape Detector (HVSD, Budney et al. 2006) at the CARE site, northwest of the King City radar.
- HVSD data were binned by particle maximum dimension, then combined in a joint histogram by size and fall speed increments of 1 cm/s.
- Observations and fits limited to particle maximum dimension, then compared in a joint histogram by size and fall speed increments of 1 cm/s.

Methodology
- The snowfall event was simulated with the WRF model, version 3.1.1, using six different single- or double-moment microphysics schemes. Forecasts use a triply nested grid configuration (5-3-1 km) with forcing provided by GPS analyses, and other parameters within Molthan et al. 2010.
- Aircraft data were separated into two vertical profiles: a descending spiral near the radar site, and descent ascent. Measured particle sizes and quantities were used to estimate moments and size distribution shape characteristics to compare against model assumptions.
- The 0600 UTC model output period was selected because observed precipitation rates were nearly steady, the radar indicated wide coverage of moderate precipitation, and each forecast produced a reasonable depiction of precipitation intensity and coverage during this period.
- WRF model vertical profiles were extracted within 50 km of the King City radar and averaged to compare model conditions across the aircraft spiral and aircraft ascent data profile.

Figure 1. Observations available during the 3DPIV intensive observation period on 22 January 2007, overlayed upon horizontally polarized radar reflectivity at 0.5°C, acquired from the dual-polarimetric, C-band radar at King City, Ontario.

Figure 2. Conditional mean profiles of hydrometeor content acquired from WRF simulated profiles within 50 km of the King City radar.

Figure 3. Conditional mean profiles of relative humidity with respect to water and ice, acquired from WRF profiles within 50 km of the King City radar.

Figure 4. a) Aircraft estimates of the size distribution intercept parameter in (1), along with model mean profiles from applicable forecast schemes. b) As in a) but for size distribution slope parameter.

Figure 5. Comparison of various PSD moments estimated from aircraft data versus mean profiles acquired from model simulated profiles.

Figure 6. Joint histogram of particle maximum dimension and fall speed from the HVSD, along with best-fit CVN/PDFV relationships and other equations used to describe fall speeds within each forecast scheme.

Implications for Simulating Remote Sensors
- Satellite simulations have been developed, generating forecasts from high resolution forecast model output (Mahrt et al. 2009).
- Model simulated profiles of hydrometeor content and remotely sensed quantities may facilitate the development of satellite-based retrievals.
- One challenge in this process is the representation of scattering by complex ice crystal shapes. Molthan et al. 2010 simulated CloudSat 4G radar reflectivity, from various non-spherical shapes and demonstrated a better fit than Mie spheres.
- To avoid mismatched assumptions, the mass-diameter relationship within the forecast model should match the characteristics of simulated crystals, such as those described by Liu (2008) and Aguiar et al. (2008).
- Mass-diameter relationships of non-unique model assumptions are compared in Figure 7a. The asymmetry parameters of two Liu 2008 crystal types are compared in Figure 7b for a variety of frequencies within the Liu 2010 database.

Figure 7. a) Mass-diameter relationships from selected forecast model simulations versus Liu 2008 dendrites and vector plates. b) Comparison of the asymmetry parameter for Liu 2008 crystal habits at a variety of frequencies.

Future Work
- Use aircraft PSDs and other CVN data sets to evaluate the simulation of satellite products for this event.
- Select a single- or double-moment scheme and incorporate flexibility in mass-diameter relationships to provide for a match to crystal database entries.
- Verify that the WRF simulated microphysics, PSDs, and crystal database entries produce reasonable mass-diameter and volume-surface quantities and attempt to use model profiles toward the retrieval of cloud properties.

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- A complete list of references is available upon request.