GCM-Oriented Ground-Observation and Phase Retrieval Forward Simulator (GO)^2-SIM

Moving Forward Towards an Apples-to-apples Comparison of Hydrometeor Phase

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Motivation

Hydrometeor phase impacts the Earth radiation budget. As GCM treatment of phase increases in complexity comes a need for evaluation and adjustment. Amongst other things, this process is complicated by observational limitations and by discrepancies between model and observational definition of hydrometeors and their phases.

Observations regardless of the platform, suffer from limitations and as such are incomplete benchmarks. Instrument forward-simulators must transform model outputs in such a way as to mimic observational limitations in order to avoid methodological biases. Only then can a comparison between simulator outputs and observations be focused on correctly diagnosing model misrepresentations.

Simulator Input-Output

(GO)^2-SIM currently interfaces with output from the Goddard Institute for Space Studies (GISS) ModelE. ModelE is a GCM with 2-moment microphysics and prognostic equations for cloud and precipitation liquid and ice.

Input: Grid-average hydrometeor:
- area fractions,
- mixing ratios,
- mass-weighted fall speeds and
- effective radii

Output: forward-simulated profiles of:
- micropulse lidar backscatter and depolarization ratio
- Ka-band radar reflectivity, mean Doppler velocity and Doppler spectrum width.

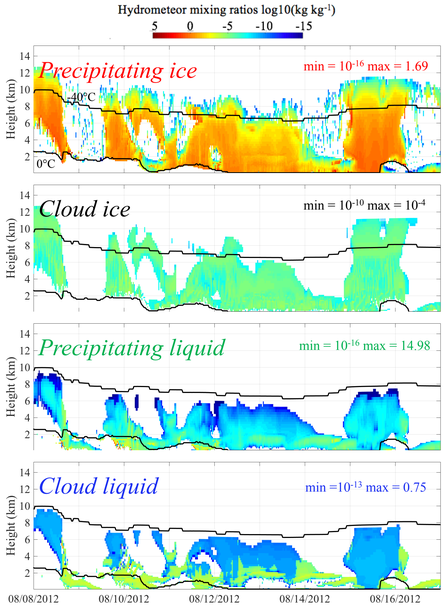

Fig. 1 Output from a 1-year global simulation for the column exacted over the North Slope of Alaska. Displayed are mixing-ratios for a) Cloud liquid b) Cloud ice c) Precip. liquid and d) Precip. ice as well as the 0 and -40°C isotherms.

Radar Simulator

(1) Convert mixing ratios to water content
(2) Use empirical relationships between water content and radar reflectivity
(3) Use liquid water content to estimate attenuation
(4) Apply range-dependent min. detectable signal
(5) Mean Doppler velocity is estimated as a reflectivity-weighted average of model hydrometeor mass-weighted fall speed
(6) Doppler spectrum width is estimated as a reflectivity-weighted average of climatological hydrometeor Doppler spectrum width

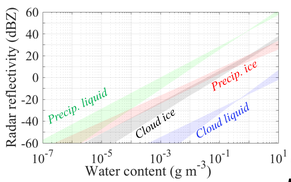

Fig.2 Spread created by using different empirical relationships to estimate radar reflectivity from water content. Multiple relationships are tested to ensure the stability of the phase retrieval.

Cloud liquid: *Sauvageot and Oman* 1987; *Fox and Illingworth* 1997; *Atlas* 1954.
Precip. liquid: *Hagen and Yuter* 2003; *Battan* 1973 or *Douglas* 1964; *Sekon and Srivastava* 1971.
Cloud ice: *Hogan et al.* 2006; *Atlas et al.* 1995; *Liu and Illingworth* 2000; *Sassen* 1987.
Precip. ice: *Hogan et al.* 2006; *Liao and Sassen* 1994; *Sato and al.* 1981; *Kikuchi et al.* 1982.

Lidar Simulator

(1) Convert mixing ratios to water content
(2) Use empirical relationships between water content and lidar extinction
(3) Convert lidar extinction to lidar backscatter
(4) Estimate optical depth from lidar extinction
(5) Use optical depth to determine laser attenuation
(6) Estimate cross-pol backscatter for cloud ice
(7) Compute depol. for liquid and ice mixtures

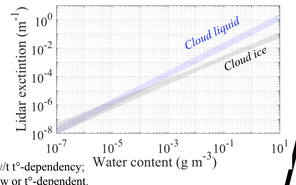

Fig.3 Spread created by using different empirical relationships to estimate lidar extinction from water content. Multiple relationships are tested to ensure the stability of the phase retrieval.

Cloud liquid: *Hu et al.* 2007.
Cloud ice: *Heymsfield et al.* 2005 w-w/t t°-dependency; *Heymsfield et al.* 2014 single power law or t°-dependent.

Forward-Simulator Evaluation, Uncertainty and Impact

Comparison with modeled mixing ratio allows the evaluation of (GO)^2-SIM.

Results indicate that only 78 % of modeled grids containing hydrometeors contain some hydrometeors detectable by radar-lidar. Moreover, mixing ratios indicate mixed-phase as the dominant phase while the instrument-simulator points to ice as the dominant phase.
⇒ **Importance to emulate instrument limitations including space varying detectability thresholds**
Our propose phase classifier leads to only 6 % error in phase determination
⇒ **Threshold techniques are robust for qualitative phase determination**
The uncertainty on the choice of empirical relationship is only 2%
⇒ **Insensitivity of qualitative phase determination on the empirical relationship used in the forward-model**

Table 1
Statistical summary of the 576 forward-simulations that use different empirical relationship combinations. Reported are amounts and percentages to the total number of hydrometeors with retrieved phase.

	Liquid			Mixed			Ice			Total hydrometeors		
Mixing ratio phase (#)	3533		-	248762		-	160426		-	412721		-
	Median		1/2 IQR	Median		1/2 IQR	Median		1/2 IQR	Median		1/2 IQR
Retrieved phase (#)	26154	±	1904	64096	±	6017	229653	±	10355	322456	±	7685
Wrong (#)	1082	±	133	3609	±	1002	160	±	62	4977	±	840
Missed (#)	522	±	47		±		4475	±	797	4977	±	840
Questionable (#)	1023	±	14		±		12584	±	2952	13613	±	2955
Total error (#)										18929	±	3631

	Liquid			Mixed			Ice			Total		
Mixing ratio phase (%)	0.86			60.27			38.87			42.07		
	Median		1/2 IQR	Median		1/2 IQR	Median		1/2 IQR	Median		1/2 IQR
Retrieved phase (%)	8.11	±	0.59	19.88	±	1.87	71.22	±	3.21	78.13	±	1.86
Wrong (%)	0.34	±	0.04	1.12	±	0.31	0.05	±	0.02	1.54	±	0.26
Missed (%)	0.16	±	0.01		±		1.39	±	0.25	1.54	±	0.26
Questionable (%)	0.32	±	0.00		±		3.90	±	0.92	4.22	±	0.92
Total error (%)										5.87	±	1.13

Forward-Simulated Fields

Forward-simulated fields at the model's native resolution can be used:
(1) for direct model evaluation against spatiotemporally resampled observations
(2) as input to a phase retrieval algorithm in a way consistent to observational techniques

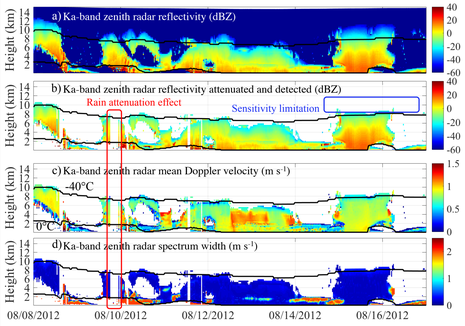

Fig.4 Example fields produced from the radar forward-simulator for one set of empirical relationships; comparable to Ka-band vertically pointing radar measurements. a) Radar reflectivity that would be observed if the radar did not suffer from attenuation and had infinite sensitivity. b-d) Radar forward-simulated fields that account for instrument limitations b) reflectivity c) mean Doppler velocity c) spectrum width. Also indicated are the 0 and -40°C isotherms.

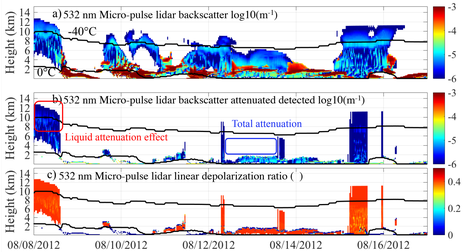

Fig.5 Example fields produced from the lidar forward-simulator for one set of empirical relationships; comparable to vertically pointing micropulse lidar measurements. a) Lidar backscatter that would be observed if the lidar did not suffer from attenuation. b-c) Lidar forward-simulated fields that account for instrument limitations b) backscatter c) linear depolarization ratio. Also indicated are the 0 and -40°C isotherms.

Using Radar Spectrum Width for Phase Classification

Low SW scenarios should indicate ice occurrence — *High SW scenarios should indicate liq. occurrence*

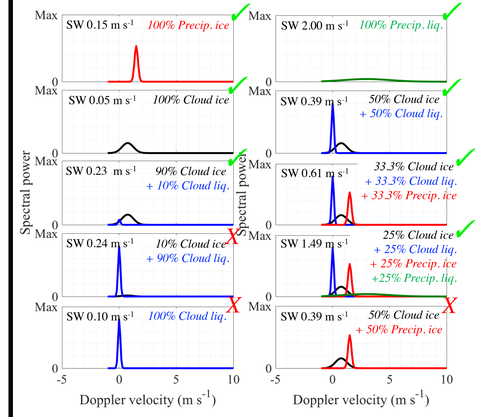

Fig. 6 Spectrum width as a tool for the identification of mixed-phase conditions above the level of lidar extinction. ✓ marks indicate that spectrum width thresholds may successfully detects phase; *X* marks indicate that spectrum width threshold would incorrectly assign phase.

Phase Map

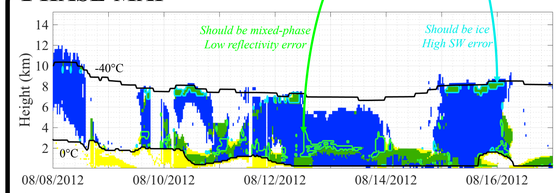

Fig. 9 Forward-retrieved phase map. Location of liquid phase (yellow), mixed-phase (green) and ice phase (blue). Outlines represent misclassifications. Also indicated are the 0 and -40°C isotherms.

Phase Retrieval

Phase Thresholds

While threshold variability is low, the best phase classification is obtained by using adjustable thresholds that best separate the "observational space" on a case-by-case basis. *An equivalent process must be applied to observations.*

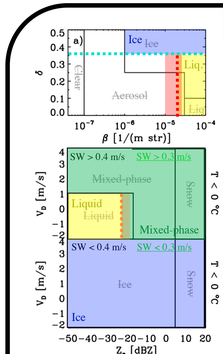

Fig. 8 Modified version of *Shupe* [2007] Multisensor phase classifier. Dashed lines represents the thresholds for this example. Shading represents IQR for 576 combinations of empirical relationships.

Isolating Different Phases in "Observational Space"

Ice and liquid drop(lets) produce measurements separated in "observational space" such that they can be isolated using thresholds.

Modeled mixing-ratio can be used to ensure the dominance of liquid in the "liquid-phase" class and the dominance of ice in the "ice-phase" class.

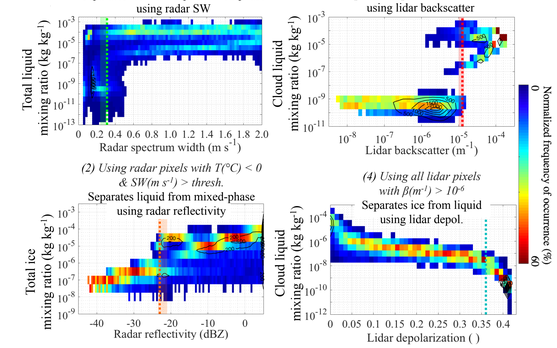

Fig. 7 Normalized frequency of occurrence of forward-simulated fields and modeled mixing ratio Dashed lines represents the thresholds that best separate distinct "populations". Shading represents IQR for 576 combinations of empirical relationships.