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Toward autonomous surface-based infrared remote sensing of polar clouds: retrievals of cloud optical and microphysical properties

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S3. CLoud and Atmospheric Radiation Retrieval Algorithm (CLARRA)

S3.3 Resolution and Model Errors

Figures S1 and S2 show examples of clear and cloud sky spectra and model errors in microwindows for 222 base cases, at resolutions of 0.1 - 20 cm^{-1}.

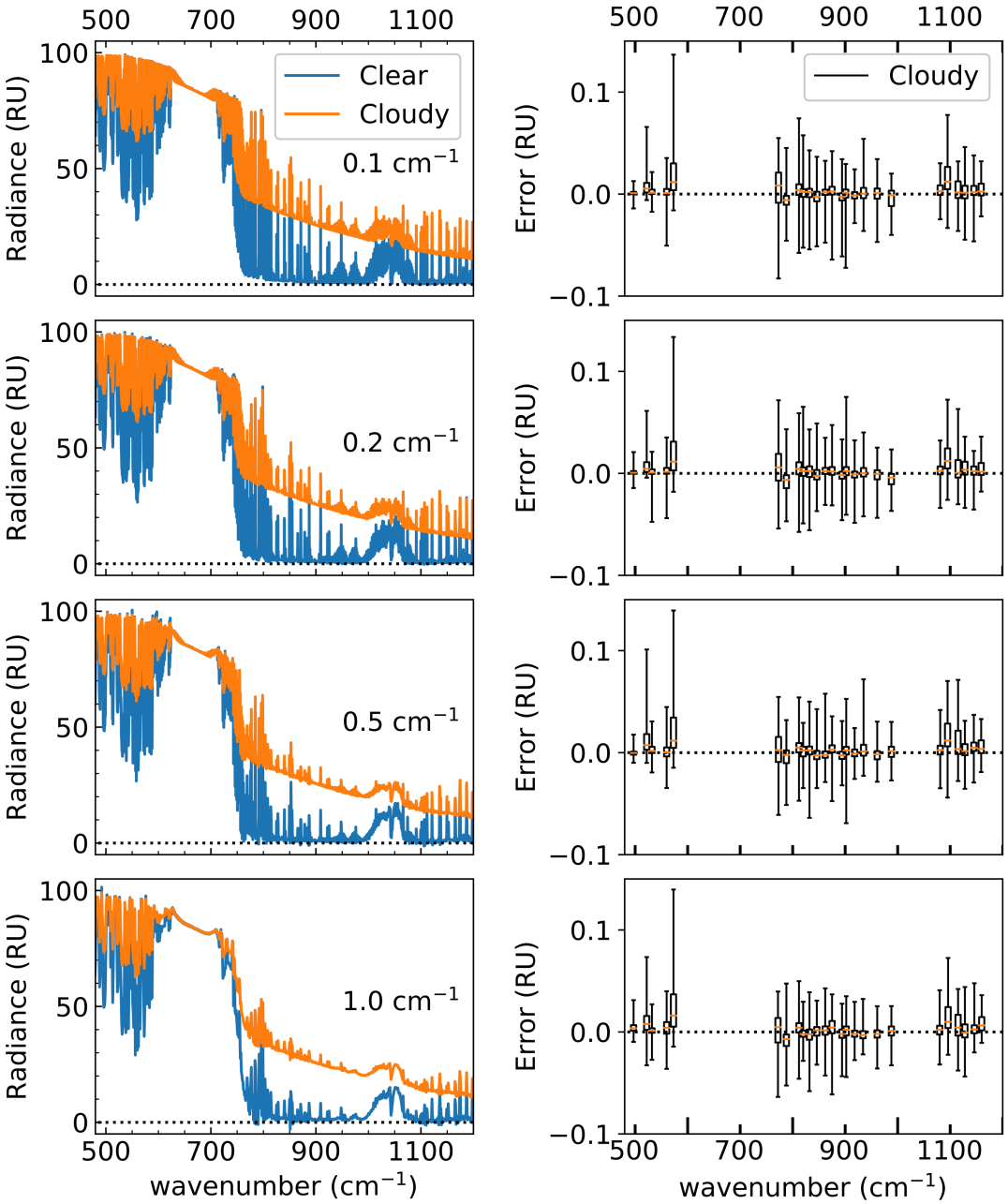

Figure S1. Clear and cloudy-sky downwelling radiances (1 RU = mW / [m^2 sr cm^{-1}]) for typical polar atmosphere (left). Box and whiskers plots of model errors (model – true) in microwindows (right; horizontal lines give the median, boxes give the 1st and 3rd quartiles, and whiskers give the range). Resolutions, given in the left-hand panels, also correspond to the right-hand panels.

(Note that the y-axis range on the right-hand side is an order of magnitude larger in Figure S2.)

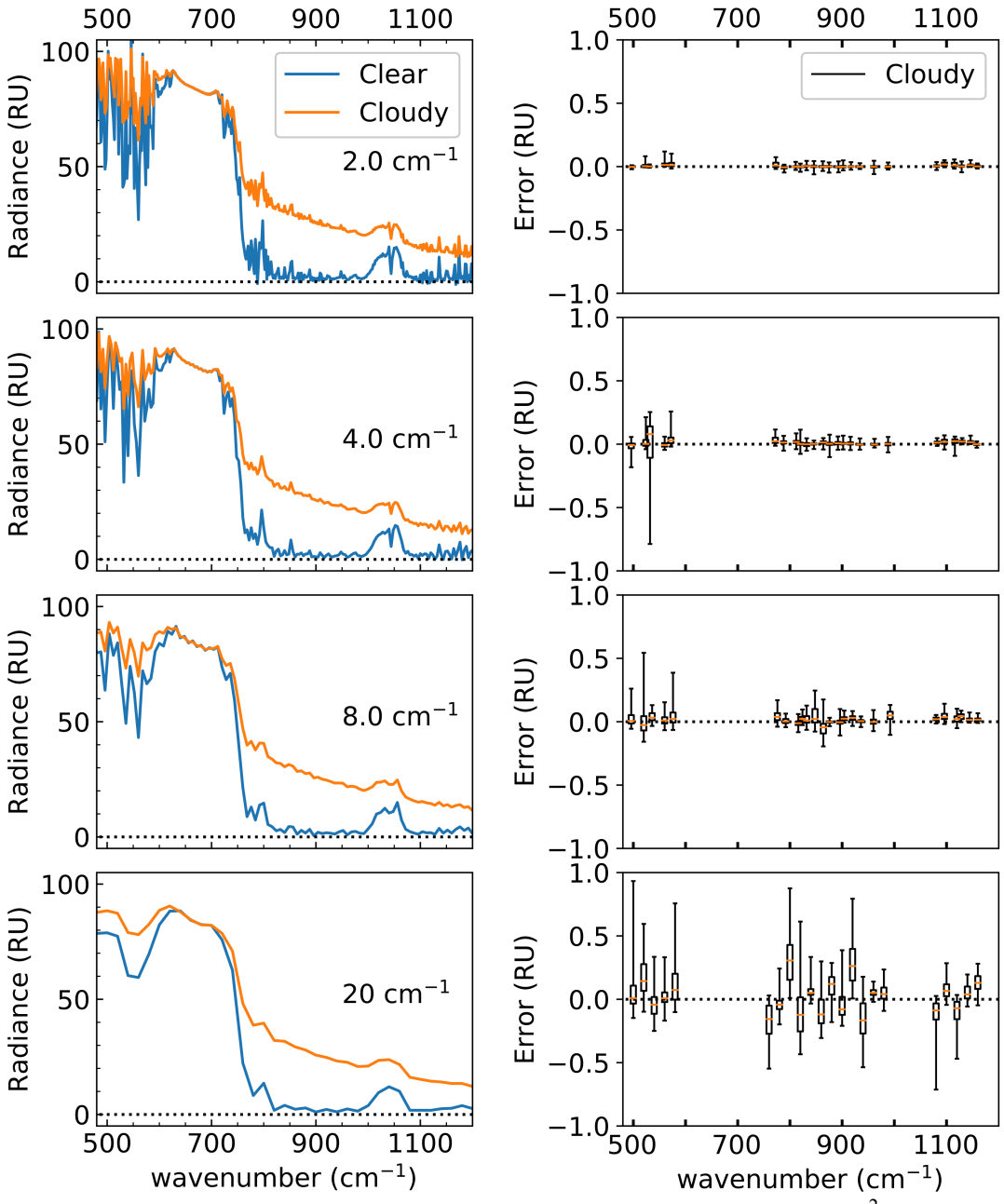

Figure S2. Clear and cloudy-sky downwelling radiances (1 RU = mW / [m^2 sr cm^{-1}]) for typical polar atmosphere (left). Box and whiskers plots of model errors (model – true) in microwindows (right; horizontal lines give the median, boxes give the 1st and 3rd quartiles, and whiskers give the range). Resolutions, given in the left-hand panels, also correspond to the right-hand panels.

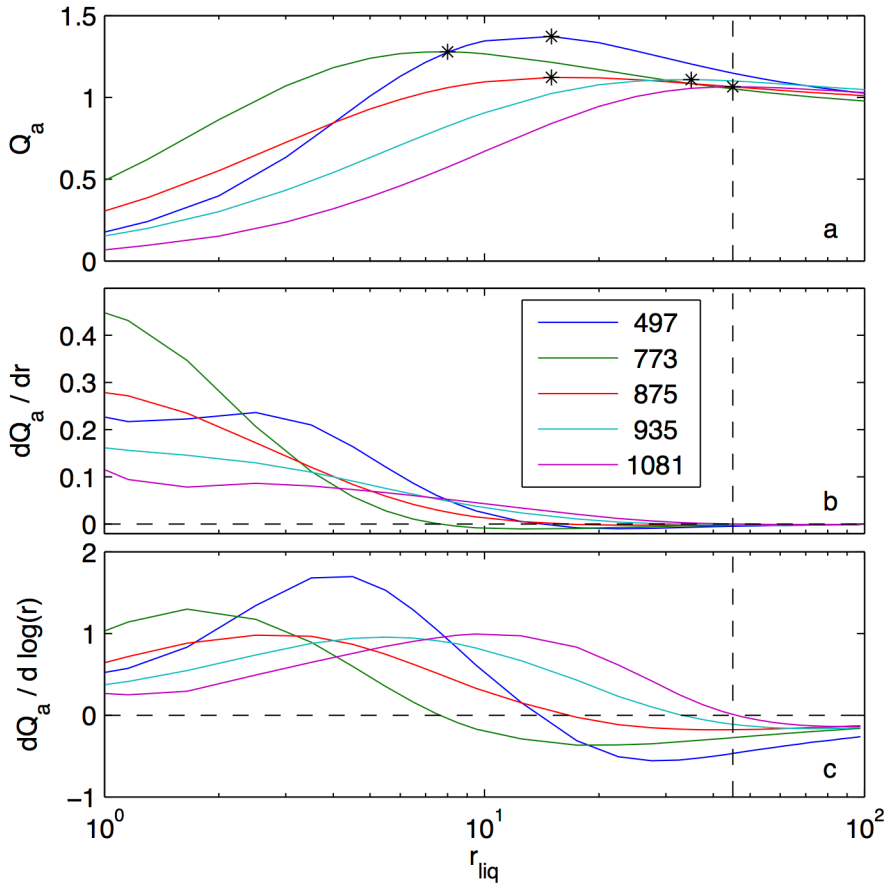

Figure S3. a) Absorption efficiency, Q_a, for spherical liquid water drops as a function of effective radius, r_{liq}. Asterisks indicate locations of maxima. b) Change in Q_a with a change in effective radius. c) Change in Q_a with a change in log of the effective radius. Results are shown for various wavenumbers, given in the legend in units of cm^{-1}.

S5. Results and Discussion

S5.1 Retrieval overview

The rational for using the log of the effective radius and for setting the maximum effective radius to ~50 µm is demonstrated through Fig. S3 for spherical liquid drops. The figure shows $Q_{abs,liq}$ as a function of effective radius r_{liq} (note that the symbol names were simplified and that the x-axis is on a log scale) at several wavenumbers. $Q_{abs,liq}$ reaches a maximum value at each wavenumber, as indicated with asterisks. At these wavenumbers and values of r_{liq}, the kernels are zero for and changes in r_{liq} have a negligible effect on τ_a; thus the retrieval lacks sensitivity to r_{liq} at the given wavenumber. The value of $Q_{abs,liq}$ for which are kernels are <= 0 is indicated with a dashed vertical line; this represents a likely limit on the value of r_{liq} that can be retrieved.

The change in radiance with a change in r_{liq} in turn depends on the change in Q_{abs} with a change in r_{liq}. However, $dQ_{abs,liq} / dr_{liq}$ is not linear, as show in Fig S3b. Instead, $Q_{abs,liq} / dr_{liq}$ decreases as r_{liq} increases. This nonlinearity causes the inverse retrieval to overestimate the step size when r_{liq} is small, resulting in potentially overstepping the solution, and underestimating the step size when r_{liq} is large, resulting in decreased sensitivity (and increased likelihood of getting "stuck" at a large value of r_{liq}. The kernels can be made more linear by modifying the kernel to $dQ_{abs,liq} / d(\log r_{liq})$, shown in Fig. S3c.

S5.2 Retrieval Errors

Table S1 shows retrieval errors for microwindow set 2 (described in main text).

Table S2 shows retrieval errors for a similar set of combined error as Table 4 of the main text, but with higher radiation bias: noise of 0.2 RU, radiation bias of 0.5 RU, water vapour bias of -3%, and temperature bias of 0.2 K (set e), the same errors but with opposite signs (set f), and the same errors as in (e) and (f) but with retrieved cloud heights (g) and (h).

Table S1. Mean and standard deviation (SD) of errors in retrieved cloud properties (where COD refers to cloud optical depth in the geometric limit and r_{liq} and r_{ice} are the effective radii of liquid and ice) for base set spectra at a resolution of 0.5 cm^{-1} and optical depth between 0.4 and 5, for microwindow set 2, with imposed errors on measurement and atmospheric state (noise and bias refers to errors in the measured radiances, and WV indicates biases in the water vapour profiles. Sources of error are microwindows are described in the text.

	COD		Ice fraction		r_{liq} (μm)		r_i (μm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
None	0.002	0.011	0.00	0.05	-0.1	0.6	0	3
Noise (0.2 RU)	0.01	0.05	0.00	0.16	0	2	1	5
WV (10%)	0.03	0.05	-0.08	0.19	0	2	3	6

Table S2. Mean and standard deviation (SD) of errors in retrieved cloud properties (COD refers to cloud optical depth in the geometric limit and r_{liq} and r_{ice} are the effective radii of liquid and ice) for base set spectra at a resolution of 0.5 cm^{-1} and optical depth between 0.4 and 5, with imposed errors on the observations as described in the text.

	COD		Ice fraction		r_{liq} (μm)		r_i (μm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Combined, e	-0.06	0.06	0.07	0.17	-1	2	-5	7
Combined, f	0.11	0.15	-0.10	0.19	0	3	5	6
Combined, g	-0.2	0.7	0.0	0.3	-1	2	-5	8
Combined, h	0.2	0.4	-0.1	0.2	1	3	5	7

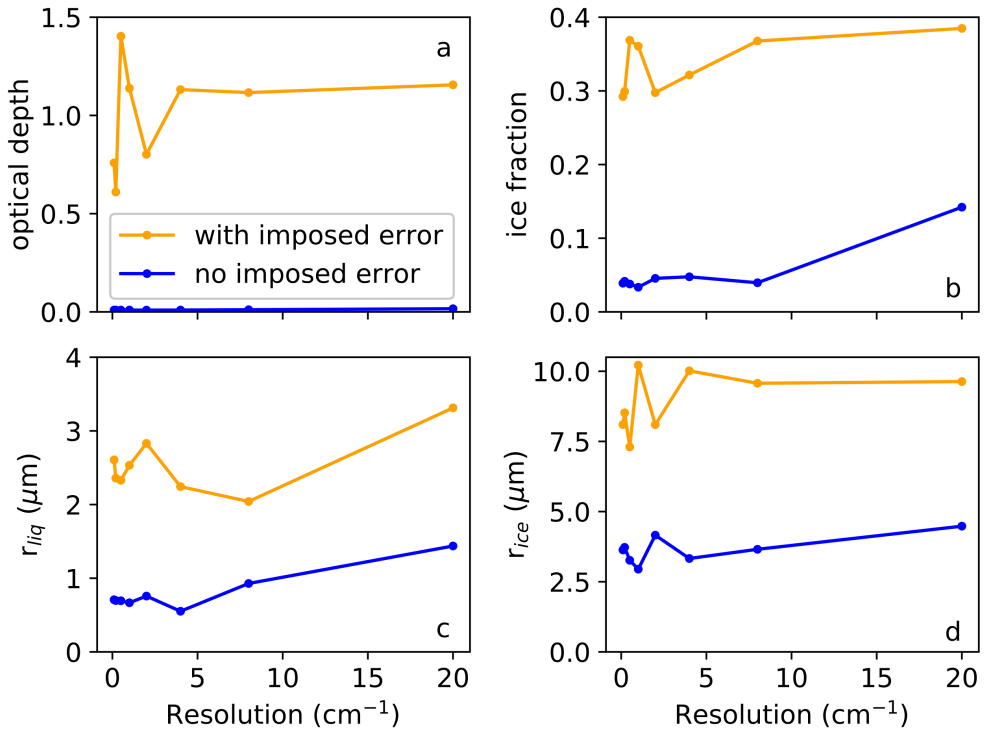

Figure S4. Root-mean-square errors in retrieved cloud properties as a function of resolution, where r_{liq} is the effective radius of liquid and r_{ice} is the effective radius of ice, for cases with and without imposed error (see text).

Figure S4 shows errors in retrieved cloud properties as a function of resolution from 0.1 to 20 cm^{-1}, for clouds with bases above 2 km, in Fig. 3. Errors are shown for base cases with no imposed error and for a combination of imposed errors: noise of 0.2 RU, radiation bias of 0.2 RU, temperature bias of 0.2 K, water vapour bias of -3%, and CHR errors in cloud height.

Figures S5 and S6 are scatter plots of retrieved vs true cloud properties for 222 base cases with imposed errors including noise of 0.2 RU, radiation bias of 0.2 RU, temperature bias of 0.2 K, water vapour bias of -3%, and CHR errors in cloud height. COD is between 0.4 and 5. The figures show combined results for clouds with bases below 2 km and for those with bases above. Instrument resolutions are 0.5 cm^{-1} (Fig. S5) and 20 cm^{-1} (Fig. S6).

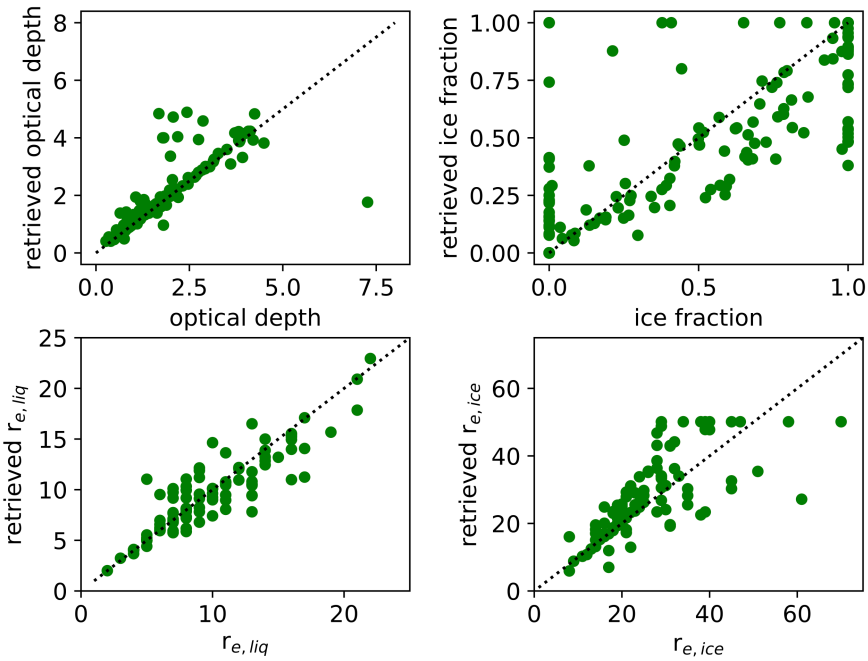

Figure S5. Retrieved vs true cloud properties for base cases with imposed errors including noise of 0.2 RU, radiation bias of 0.2 RU, temperature bias of 0.2 K, water vapour bias of -3%, and CHR errors in cloud height, at a resolution of 0.5 cm^{-1} for clouds with COD between 0.4 and 5.

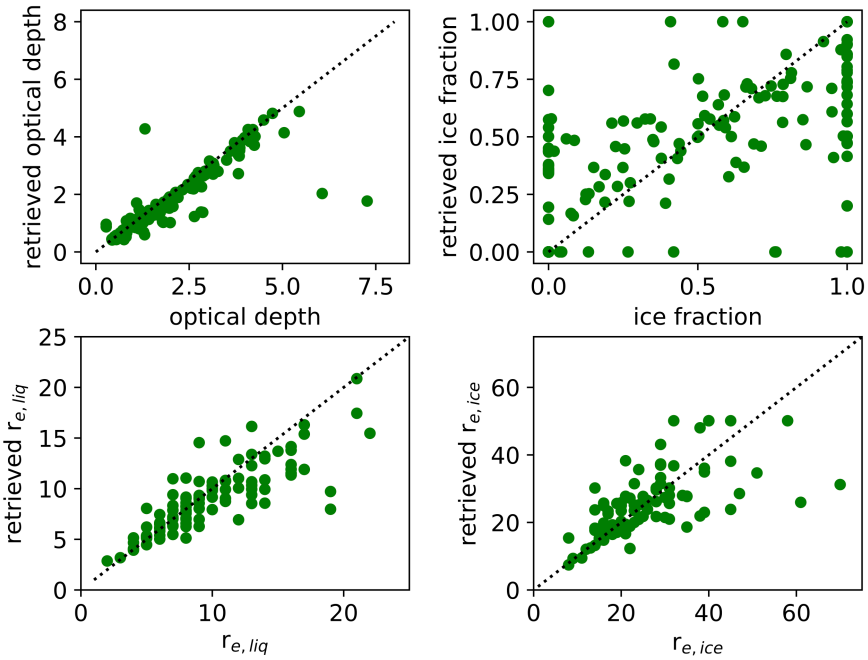

Figure S6. Retrieved vs true cloud properties for base cases with imposed errors including noise of 0.2 RU, radiation bias of 0.2 RU, temperature bias of 0.2 K, water vapour bias of -3%, and CHR errors in cloud height, at a resolution of 20 cm^{-1} for clouds with COD between 0.4 and 5.

S5.4 Cloud vertical inhomogeneity and Ice habit

Tables S3 and S4 show retrieval errors for a similar combinations of imposed error as in the main text, but with a higher radiation bias (i.e. noise of 0.2 RU, radiation bias of 0.5 RU, water vapour bias of -3%, and temperature bias of 0.2 K). The upper set uses true cloud heights, while the lower set uses retrieved cloud heights. Trends are similar as for the error combinations given in the main text.

Table S3. Errors in retrieved cloud properties for macroscopically varying clouds at a resolution of 0.5 cm^{-1}, for several combinations of error imposed on the observations (see text). COD refers to cloud optical depth in the geometric limit, r_{liq} and r_{ice} are the effective radii of liquid and ice, and SD indicates standard deviation.

Cloud type	Error	COD		Ice fraction		r_{liq} (μm)		r_{ice} (μm)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dense	y	-0.05	0.05	0.08	0.11	-1	2	-5	8
Diffuse	y	-0.04	0.04	0.13	0.14	-1	2	-6	8
Inhomogeneous	y	-0.04	0.04	0.11	0.11	-1	2	-4	7
Liquid topped	y	0.01	0.05	0.08	0.14	-1	2	-1	8
Dense	y*	-0.08	0.13	0.12	0.13	-1	2	-6	11
Diffuse	y*	-0.04	0.07	0.12	0.12	-1	3	-6	13
Inhomogeneous	y*	-0.04	0.09	0.14	0.13	-2	2	-6	11
Liquid topped	y*	-0.06	0.13	0.14	0.12	-1	2	-4	10

Table S4. Errors cloud properties retrieved assuming a spherical ice habit, for ice clouds of varying habit (first column), when error is imposed on the observations (see text). COD refers to cloud optical depth in the geometric limit, r_{liq} and r_{ice} are the effective radii of liquid and ice, and SD indicates standard deviation.

Habit	Error	COD		Ice fraction		r_{liq} (μm)	
		Mean	SD	Mean	SD	Mean	SD
Sphere	y	-0.06	0.03	0.14	0.10	-4	8
Hollow bullet rosette	y	0.4	0.3	0.06	0.10	5	5
Smooth solid column	y	0.2	0.2	0.08	0.09	2	4
Rough solid column	y	0.2	0.2	0.04	0.07	2	4
Smooth plate	y	0.4	0.3	0.04	0.08	5	3
Rough plate	y	0.4	0.3	0.08	0.10	4	3
Sphere	y*	-0.4	0.7	0.15	0.11	-6	3
Hollow bullet rosette	y*	0.1	0.8	0.17	0.14	0	8
Smooth solid column	y*	-0.2	0.8	0.17	0.10	-2	7
Rough solid column	y*	-0.2	0.8	0.15	0.10	-2	4
Smooth plate	y*	0.0	0.8	0.15	0.12	0	9
Rough plate	y*	0.0	0.8	0.2	0.11	-1	8