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# Impact of conditional sampling and instrumental limitations on the statistics of cloud properties derived from cloud radar and lidar at SIRTA

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[1] Clouds represent the largest uncertainty in future climate projections. As a result, unbiased long-term vertically-resolved cloud observations must be collected and analyzed in order to produce regional cloud climatologies. In the present study, we use model outputs to evaluate the impact of conditional temporal sampling and instrumental effects on the 2-year statistics of frequency of cloud occurrence and cloud fraction. We then quantify the radiative significance of the ice clouds undetected by cloud radars. We find that in order to evaluate the representation of all types of clouds in operational models both a cloud radar and a lidar must be used. The cloud radar alone can do a reasonable job at describing cloud properties up to 8–9 km, however the lidar is mandatory to detect most of the high-altitude clouds above 9 km. The sampling should be regular but not necessarily continuous, and should not be driven by meteorological conditions. This result applies to all sites having a lidar without a radome. It is finally suggested that a cloud radar of around –60 dBZ sensitivity at 1 km range would be required to detect almost all radiatively-significant ice clouds. **Citation:** Protat, A., A. Armstrong, M. Haeffelin, Y. Morille, J. Pelon, J. Delanoë, and D. Bouniol (2006), Impact of conditional sampling and instrumental limitations on the statistics of cloud properties derived from cloud radar and lidar at SIRTA, *Geophys. Res. Lett.*, 33, L11805, doi:10.1029/2005GL025340.

## 1. Introduction

[2] Clouds represent the largest uncertainty in future climate projections. In this respect, ground-based remote sensing observatories have a crucial role to play in providing data in order to improve our understanding of atmospheric processes and the performance of atmospheric models at all scales. Recently accurate climatologies have been obtained over the US and Europe using active remote sensing [e.g., Mace *et al.*, 2001; Hogan *et al.*, 2001; Wang and Sassen, 2002]. In this framework, the CloudNet project [Illingworth and the CloudNET Team, 2004] was established with three objectives: (i) to collect remotely sensed cloud data quasi-continuously from a network of three cloud remote sensing stations and simultaneously gather hourly vertical profiles from four major operational models over the stations; (ii) to develop and validate state-of-the-art

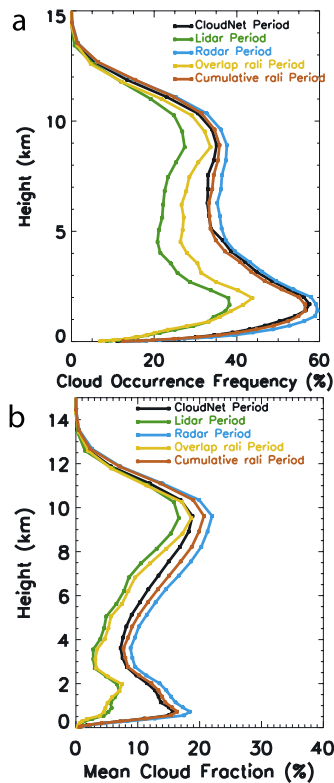
techniques for accessing the microphysical cloud properties from cloud radar, lidar, and microwave radiometer observations; and (iii) to develop regional cloud climatologies from observations to evaluate the representation of clouds in operational weather forecast models (in particular the fraction of the grid box that is filled with clouds, named the “cloud fraction”, and the ice water content). During the period October 2002–October 2004 three stations located at Chilbolton (United Kingdom, 51°N, 1°E), Cabauw (Netherlands, 52°N, 5°E), and Palaiseau (SIRTA, France, 48°N, 2°E) operated cloud radars, visible and near-IR lidars, ceilometers and dual wavelength microwave radiometers on a continuous and/or routine schedule.

[3] Several studies have shown that routine monitoring of clouds from ground-based stations provided valuable data sets for atmospheric model evaluation and development of parametric representation of cloud processes [e.g., Morcrette, 2002; Guichard *et al.*, 2003; Chiriaco *et al.*, 2006]. A major difficulty in the exploitation of observations to evaluate model performance is however due to the potential inconsistencies between simulations and observations. In particular, inconsistencies due to conditional sampling and limited instrument sensitivities may arise because the observation system is not capable to sample the entire atmospheric column at all times.

[4] During CloudNet the station in Palaiseau (SIRTA: Site Instrumental de Recherche par Télédétection Atmosphérique) [Haeffelin *et al.*, 2005] operated a 94 GHz cloud radar, a near-IR low output ceilometer, a visible/near-IR high output cloud lidar, and a 2-channel microwave radiometer. The cloud radar and lidar at SIRTA were not originally designed for unattended operational use. As the lidar system is not protected from precipitation damage, periodic verification by operators is required, and the lidar cannot operate if precipitation reaches the ground. As a result, the temporal sampling of lidar observations is mostly limited to daytime and to periods with low risk of precipitation. In the period 10/2002–09/2003 radar and lidar observations were on a very similar schedule. From 10/2003 to 10/2004, radar observations were progressively increased to 24h per day, 7 days per week.

[5] Biased sampling could also be caused by the instrument sensitivities. For the lidar, the occurrence of a water cloud below an ice cloud will lead to total extinction of the lidar signal by the strong scattering by the water cloud droplets and any ice cloud above will not be detected. Similarly, cloud radars do not detect all thin high-altitude ice clouds due to their limited sensitivity [Iwasaki *et al.*, 2004]. Such clouds are generally considered as radiatively

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**Figure 1.** Vertical profile (0–15 km) of the frequency of (a) cloud occurrence (ratio at each level of the total number of “cloudy” hours to the total number of observational hours, with the whole cloudy hour assumed to be filled with clouds) and (b) cloud fraction (fraction of each model grid box filled with clouds). The black line (labeled “CloudNet period”) corresponds to the “reference” profile obtained from the 24 months of ECMWF profiles. The other profiles are derived from the lidar (green), radar (blue), coincident radar-lidar hours (hours when both the radar and the lidar operate, orange line), and cumulative radar-lidar hours (hours when either the radar or the lidar or both operate, red line) of operations.

important when their optical depth is larger than 0.05 [Brown and Francis, 1995].

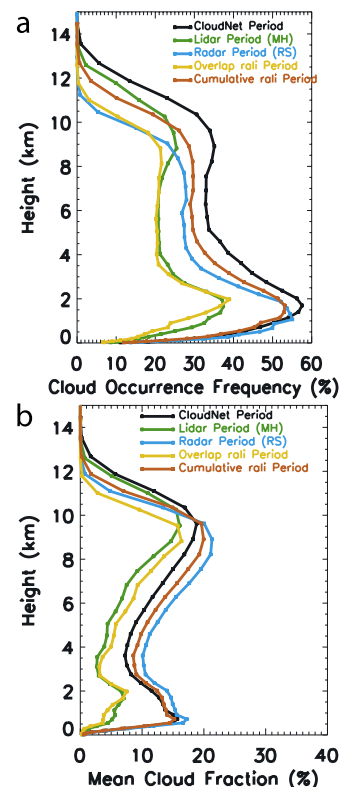
[6] In this paper, we evaluate the impact of the conditional temporal sampling (section II) and instrumental effect (section III) on the 2-year statistics of frequency of cloud occurrence and cloud fraction using model outputs. The radiative significance of the high-altitude ice clouds undetected by cloud radars of different sensitivities is then evaluated in section IV.

## 2. Impact of Conditional Sampling on Cloud Properties

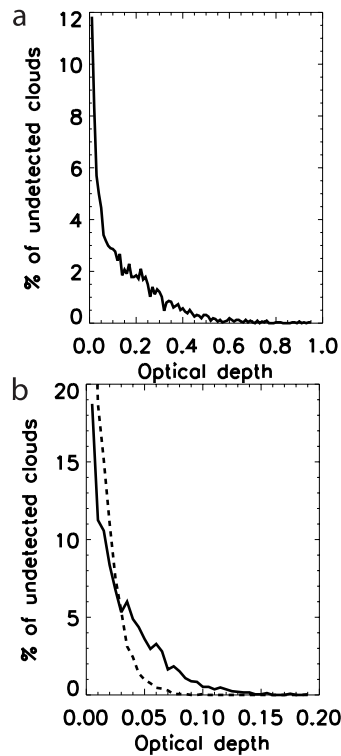
[7] The impact of the partial temporal sampling on the cloud property statistics is evaluated using numerical weather forecast model runs. For this study, we used 24 months of the hourly ECMWF analysis of the cloud fraction parameter (30 km grid box, 60 vertical levels) in the vertical column located above SIRTAs as the “reference”

(Figure 1). It is therefore the main assumption of this study that the ECMWF model correctly represents clouds, at least in a statistical sense. Latest results from the CloudNet project indicate that this is the case [Illingworth and the CloudNET Team, 2004]. The other vertical profiles of Figure 1 are shown without including any instrumental effect in order that the effect of partial temporal sampling is evaluated in a first step as a distinct source of error.

[8] The vertical profiles of cloud occurrence and cloud fraction (Figure 1) for the different sampling hours reveal that while the radar observational sampling (around 1/3 of the total time) does not cause significant biases in the retrieval of the vertical column, the use of the lidar observation schedule (and hence the coincident lidar-radar hours) produces a significant bias toward situations with less cloudy columns (more clear-sky operations than with 24-7 sampling). To investigate if the bias of the lidar-only and coincident radar-lidar profiles is simply due to the limited number of lidar hours (around 1/7 of the total time) we derived a set of the same number of vertical profiles by regularly sampling the ECMWF data set every 7 days (not shown). Such an infrequent but regular sampling does not reproduce the biases of Figure 1, although it slightly increases the random error (this was verified using shifted sampling). This result clearly shows that these biases are attributable to the fact that the mode of operation favors the observation of atmospheric conditions with less clouds of lower liquid water content to prevent risk of damage from precipitation. In conclusion, in order to produce vertical profiles of cloud properties unbiased with respect to conditional sampling, the sampling should be regular but not



**Figure 2.** Same as Figure 1, but with radar and lidar instrumental effects added.



**Figure 3.** Histograms of the optical depth of the ice clouds undetected by a radar of sensitivity (a)  $-45$  dBZ, (b)  $-55$  dBZ (solid) and  $-60$  dBZ (dashed) at 1 km range. Note the change in scale between Figures 3a and 3b. The total number of profiles from which the percentages are computed is 5979.

necessarily fully continuous, and should not be driven by meteorological conditions.

### 3. Impact of Instrumental Effects on Cloud Statistics

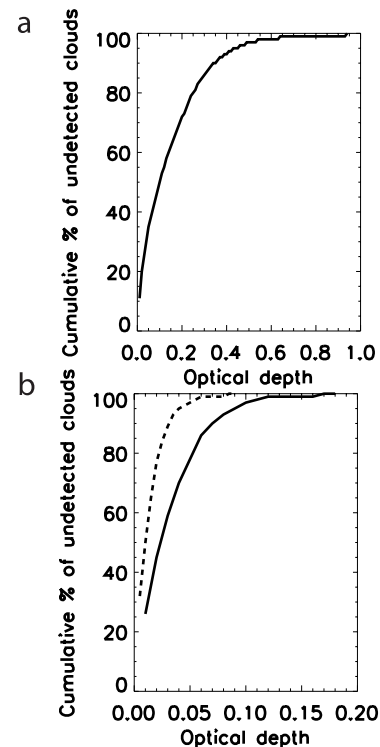
[9] Additional errors are to be expected due to instrumental effects. The most significant effect is due to instrumental sensitivities. Lidar signals are strongly attenuated by scattering through liquid water clouds and optically thick ice clouds. The presence of such optically thick layers at low altitudes will prevent the ground-based lidar from detecting higher altitude clouds. This lidar instrumental effect is accounted for by limiting further the retained lidar hours of operations to the heights where the true observed lidar signal at SIRTa is above a signal-to-noise ratio threshold. On the other hand, it is now recognized that owing to their limited sensitivity the cloud radars do not detect all the high-altitude, thin ice clouds [e.g., Iwasaki *et al.*, 2004]. In order to account for the latter effect, the model ice water content has been converted into an equivalent 95 GHz radar reflectivity using the statistical relationship of Liu and Illingworth [2000] and the reflectivities below the SIRTa cloud radar sensitivity have been removed from the radar hours of operations to compute new profiles of cloud occurrence and cloud fraction. No attempt has been made to do the same for water clouds, as previous studies have shown that a radar of  $-40$  dBZ sensitivity should be able to

detect all stratocumulus clouds [Fox and Illingworth, 1997]. The coincident and cumulative lidar-radar hours of operations are also recomputed from the remaining lidar and radar hours of operations. Figure 2 shows the same plots as those of Figure 1, this time including the additional instrumental effects. This figure shows that the radar or cumulative radar-lidar profiles are the most accurate estimates of frequency of cloud occurrence up to 9–10 km altitude (Figure 2a) and of cloud fraction up to 10 km altitude (Figure 2b), at which point, from 9–10 and up to 13 km in altitude the lidar-only profile is the most accurate estimate of the frequency of cloud occurrence and cloud fraction.

[10] It is noteworthy that the same analysis using the UK Meteorological Office Unified Model instead of the ECMWF model led to the same overall conclusions (results not shown), implying that the effects shown in Figure 2 do not appear to be model-dependent. It is thus shown that in order to evaluate the representation of clouds in operational models it is important to use both a cloud radar and a lidar, due to their instrumental complementarity. The cloud radar alone can do a reasonable job at describing clouds up to 8–9 km (with the cumulative radar-lidar being more accurate), however the lidar is mandatory to detect high-altitude clouds that range between 9 and 15 km.

### 4. Radiative Impact of the Ice Clouds Undetected by the Cloud Radars

[11] As previously discussed cloud radars fail to observe a significant amount of the ice clouds situated above 8–9



**Figure 4.** Cumulative distribution of the clouds undetected by a radar of sensitivity (a)  $-45$  dBZ, (b)  $-55$  dBZ (solid) and  $-60$  dBZ (dashed) at 1 km range as a function of their optical depth. Note the change in scale between Figures 4a and 4b.

km height due to their limited sensitivity. The examples discussed in the previous sections were obtained with the SIRTA cloud radar, the mean sensitivity of which during CloudNet was approximately  $-45$  dBZ at 1 km range over the two years of operation.

[12] Although these high-altitude ice clouds do not have a strong meteorological impact, they have a significant impact in terms of climate change due to their influence on the net radiation budget at the top of atmosphere: an optical depth of 0.05 leads to a  $10 \text{ W.m}^{-2}$  net radiative impact [Brown and Francis, 1995]. This study offers the opportunity to investigate more quantitatively the radiative impact of these undetected ice clouds. To do so, we retain all ice clouds that are below two different radar sensitivity thresholds (by converting as in section 3 the model IWCs into synthetic radar reflectivities using the Liu and Illingworth [2000] relationship, as done in section 3). The estimated accuracy on  $Z$  depends on the magnitude of IWC. It is around 3 dBZ in average, which translates into about the same error for the computation of  $Z$ . Next we use the same effective radius parameterization as in the ECMWF model to estimate visible extinction as  $\alpha = (3/(2\rho_w)) \text{ IWC}/R_e$ , where  $\rho_w$  is the density of liquid water, and integrate it over the cloud depth to compute the optical depth of the undetected ice clouds. The histogram of these optical depths is given in Figure 3a for the mean SIRTA cloud radar sensitivity and for the initial SIRTA cloud radar sensitivity (assuming no power loss for the 95 GHz tube during CloudNet, that is,  $-55$  dBZ at 1 km range). The histograms clearly show that a significant amount of radiatively-important ice clouds is not observed by a cloud radar of  $-45$  dBZ sensitivity at 1 km range, which is not the case for the cloud radar of  $-55$  dBZ sensitivity at 1 km range.

[13] From Figure 4 it is obtained that 64.7 % of ice clouds of optical depth larger than 0.05 remain undetected by a cloud radar of sensitivity  $-45$  dBZ at 1 km. This amount is still 49.3 % for the undetected clouds above an optical depth of 0.1. With a cloud radar of sensitivity  $-55$  dBZ at 1 km, around 20% of radiatively-significant ice clouds (above the 0.05 threshold) remain undetected. However, only 3% of the undetected ice clouds are of optical depth greater than 0.1. Therefore, although cloud radars of  $-55$  dBZ sensitivity at 1 km still fail to detect a significant portion of ice clouds, the optical depth of which mostly ranges from 0.05 and 0.1, they should be able to detect almost all clouds (97%) of optical depth greater than 0.1. In order to conclude this sensitivity study, we have computed in Figures 3b and 4b the histogram and cumulative distribution of optical depth for a cloud radar of  $-60$  dBZ sensitivity at 1 km. In this case, only 2.1 % of the radiatively-significant ice clouds are not detected, and none of optical depth greater than 0.1. Therefore, in conclusion to this sensitivity study, we state that a radar of  $-60$  dBZ sensitivity at 1 km should be able to detect almost all (98%) ice clouds of significant radiative impact.

## 5. Conclusions

[14] The objectives of this work were to evaluate the impact of conditional temporal sampling and instrumental

effects on the 2-year statistics of frequency of cloud occurrence and cloud fraction using ECMWF model analyses as a reference, which was the main assumption of this study. We find that in order to evaluate the representation of clouds in operational models the use of both a cloud radar and a lidar is imperative. The cloud radar alone can reasonably describe cloud properties up to 8–9 km, however the lidar is mandatory to detect high-altitude clouds above 9 km, which are often optically thin. The sampling should be regular but not necessarily continuous, and should not be driven by meteorological conditions. Based on this sensitivity analysis it is also suggested that a cloud radar with a sensitivity of  $-60$  dBZ at 1 km or better would be required to detect almost all (98%) radiatively-significant ice clouds.

[15] **Acknowledgments.** This work has been funded by the European Union CloudNet project under contract EVK2-CT- 2000-00065, and supported by the Centre National d'Etudes Spatiales (CNES). We are also indebted to the SIRTA technicians and engineers who took care of the instruments during CloudNet, and to Adrian Tompkins (ECMWF), who provided CloudNet with the ECMWF profiles used in the present study. The SIRTA is supported by Ecole Polytechnique, CNES, and IPSL.

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