GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 11, 1578, doi:10.1029/2003GL017163, 2003

In-cloud variability of LIDAR depolarization of polar and midlatitude cirrus

Massimo Del Guasta
Istituto di Fisica Applicata "Nello Carrara" (IFAC) CNR, Florence, Italy

Edgar Vallar
Physics Department, De La Salle Univ., Manila, Philippines

Received 20 February 2003; revised 23 April 2003; accepted 6 May 2003; published 10 June 2003.

[1] LIDAR depolarization is commonly used for discriminating liquid and ice particles. Since depolarization depends in a complicated manner on particle shape and size, in-cloud variability of depolarization has been used as an indicator of the microphysical homogeneity of cirrus. The comparison between midlatitude (Florence, Italy, 43. 60°N) and polar (Dumont d'Urville, Antarctica, 66. 68°S) cirrus showed a lower mean depolarization and a higher in-cloud uniformity of cloud depolarization for polar clouds in the (−80, −50°C) temperature range. A wider in-cloud variability of depolarization was observed in polar clouds at higher temperatures (−50, −30°C), reflecting the presence of supercooled liquid layers. The large in-cloud variability of depolarization in Florence cirrus could be explained with a microphysics that is dynamically and chemically perturbed as compared with the polar site. Aged jet contrails are, in fact, present in many Florence cirrus records. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0669 Electromagnetics: Scattering and diffraction; 1640 Global Change: Remote sensing. **Citation:** Del Guasta, M., and E. Vallar, In-cloud variability of LIDAR depolarization of polar and midlatitude cirrus, *Geophys. Res. Lett.*, *30*(11), 1578, doi:10.1029/2003GL017163, 2003.

1. Introduction

[2] Cirrus clouds continue to receive considerable attention from the scientific community because of their role in modulating the Earth's climate through direct and indirect radiative forcing. Polarization LIDARs have been a very effective instrument in studying not only the spatial and temporal variability of these clouds but also their thermodynamics, particle shape and orientation [*Sassen*, 1991]. LIDAR depolarization is among the best indicators of cloud particle asphericity [*Sassen*, 1991]. Recent statistics of cirrus depolarization are available. By using a ~6-year subset of ruby LIDAR zenith and off-zenith measurements from the FIRE ETO dataset, *Sassen and Benson* [2001] investigated the dependence of the linear depolarization ratio on different parameters such as height, temperature, LIDAR orientation, together with particle shape and orientation. TOGA/COARE airborne polarization LIDAR data from January–February 1993 showed a consistent increase of the average linear depolarization ratio with altitude [*Sassen et al.*, 2000]. *Del Guasta et al.* [1993] used the Dumont d'Urville 532 nm cloud LIDAR data from 1989 to infer a similar behavior of depolarization with temperature. The magnitude of cloud depolarization has been related to ice crystal shape and orientation in a large number of experimental studies and in numerical ray-tracing computations. As a general result of these studies, no unique correlation between depolarization value and crystal shape/size/orientation is usually possible in the absence of in-situ data (and this is, unfortunately, a condition necessarily encountered in most long-term LIDAR studies). Nevertheless, it is possible to infer microphysical information of statistical relevance by studying the depolarization variability along the cloud profile: Since different particles can produce different depolarization values, the presence of depolarization fluctuations within a cirrus cloud clearly indicates the inhomogeneous nature of the particle population in terms of size/shape/orientation. On the other hand, the absence of fluctuations may indicate either the microphysical homogeneity of the cloud or the ubiquitous presence in the cirrus of particles (e. g., pristine hexagonal crystals) characterized by a high depolarized-backscatter efficiency [*Del Guasta*, 2001]. In this work, the analysis of in-cloud variability of depolarization was applied to two extensive LIDAR datasets obtained, respectively, from the midlatitudes (Florence, Italy, 43. 60°N) and from a polar site (Dumont d'Urville, Antarctica, 66. 68°S). The two LIDAR systems were practically identical and were operated using very similar protocols. This makes it possible to have a consistent statistical comparison of the two cirrus datasets in terms of depolarization values and in-cloud depolarization fluctuations.

2. Methods

[3] 532 nm data from the polarization LIDAR systems operating in Dumont d'Urville and in Florence were used in this work. Both LIDARs are zenith-pointing systems that employ a 10 Hz repetition rate Nd:YAG laser with outputs at 532 nm (300 mJ, linearly-polarized) and 1064 nm (400 mJ, circularly-polarized). The LIDAR receivers were 80 cm-diameter Cassegrain telescopes with a ≈1 mrad FOV and equipped with 0. 15 nm bandwidth interference filters at 532 nm. The 532 nm-backscattered signals, detected by PMTs, were digitized by a LeCroy digitizer and had a 30–75 meter resolution. Further technical details regarding the two systems can be found in *Stefanutti et al.* [1992a] and

0094-8276/03/2003GL017163$05.00

Stefanutti et al. [1992b], respectively. In both the Florence (FLR) and the Dumont d'Urville (DDU) systems, LIDAR signals were averaged over a period of 1 minute and were post-processed using the procedure described by *Morandi* [1992] and *Del Guasta et al.* [1993] to obtain calibrated vertical backscatter profiles.

[4] The calibrated volume backscatter [$m^{-1}sr^{-1}$] including the molecular scattering (β') and the aerosol volume backscatter component (β) were calculated. The molecular component (determined with the use of PTU soundings) was removed point by point from β' to obtain β. No extinction corrections were performed because cirrus depolarization is relatively unaffected by extinction [*Sun et al.*, 1989].

[5] The FLR (year 2000–2001) and DDU (year 1994–1996) datasets contained 34 and 51 cirrus events, respectively. The duration of each event was variable, ranging between 15 minutes minimum and several hours. Each FLR cirrus measurement had between 1,961 to 35,340 measurement points while DDU records contained 444–13,020 points each. Two different depolarization values were calculated in each cirrus dataset:

[6] The total linear depolarization ratio

$$\sigma' = \frac{\beta'_s}{\beta'_p}$$

was computed point-by-point for the comparison of our results with data in the literature (suffixes p and s indicate the backscattered light polarized parallel and perpendicular to the linear polarization of the laser beam).

[7] The mean aerosol linear depolarization ratio

$$\sigma = \left\langle \frac{\beta_s}{\beta_p} \right\rangle$$

was also calculated for each cirrus event. δ was computed as the slope of the linear fit of the $\beta_p - \beta_s$ scatter plot for each cirrus event. In the calculation of both δ and δ', noisy points randomly distributed around the axis origin were removed from the $\beta_p - \beta_s$ plot by applying a circular filter of constant radius centered at the origin. The standard deviation (σ_δ) [*Edwards*, 1984] of the slope δ and the number (n) of data points for each cirrus event were used in calculating the quantity:

$$\varepsilon = \sqrt{n} \bullet \sigma_\delta / \delta$$

This quantity is $\sqrt{n}$ times the relative, standard error of the mean slope δ. This definition for the spreading of $\beta_p - \beta_s$ around the fitting line is independent of the number of sampled points (because of the $\sqrt{n}$ factor) and of the uncertainties of p-s channel intercalibration (because of the normalization to δ).

[8] Channel intercalibration is very important in determining the depolarization values recorded in different LIDAR stations and does not follow any international standard. For its measurement, some authors rely on the theoretical Rayleigh linear depolarization from the clean atmosphere while others prefer to send unpolarized or circularly-polarized light into the telescope. These different methods certainly contribute to the variability of worldwide-observed cirrus depolarization but would have no influence on ε values. For this study, the same calibration technique was used in both LIDAR sites and involves placing a $\lambda/4$ plate at the output of the Nd:YAG laser in order to produce a circularly polarized 532 nm laser beam.

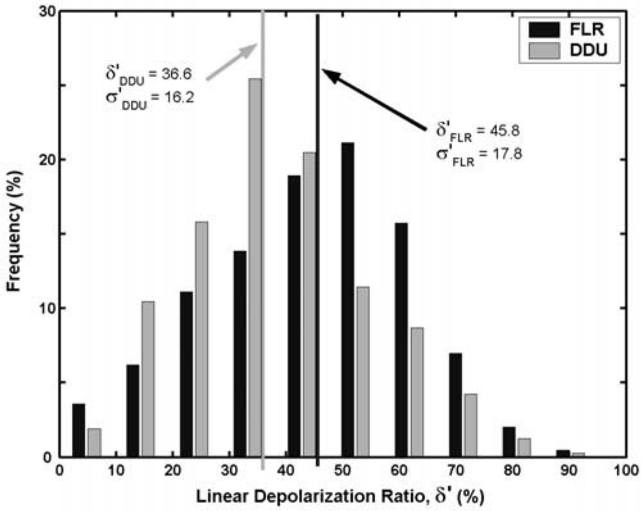

Figure 1. Histogram of point-by-point δ' depolarization values for DDU and FLR. The median and SD of δ' values are also shown.

[9] Since Florence is located under a busy air corridor, fresh contrails were spotted with the help of visual and webcam observations. Contrails were also identified in the time-height-backscatter plots on the basis of their limited vertical extent and marked backscatter compared with the surrounding cirrus. Evident contrails were arbitrarily excluded from the statistical analysis as they sometimes showed LIDAR characteristics different from those of "undisturbed" cirrus [*Del Guasta and Niranjan*, 2001].

[10] Point-by-point temperature data for FLR cirrus were taken , assuming a few degrees of uncertainty, from the daily PTU soundings at San Pietro Capofiume (44.65°N, 11.62°E), located approximately 100 km NE downstream from the FLR site. DDU PTU data were obtained using local soundings. Midcloud temperatures were computed as the average of the respective temperatures for the cirrus base and top heights.

3. Results

3.1. Depolarization Statistics

[11] The histogram of the δ' depolarization values for DDU and FLR cirrus are shown in Figure 1. A positive skewness for DDU data and a negative skewness for FLR data was found. This asymmetry showed the predominance of low depolarization points in DDU cirrus data and the opposite type of behavior in FLR data. The two medians were also different, with FLR cirrus data typically showing a higher depolarization than the DDU data. Figure 2 illustrates the same statistics but resolved in temperature together with some statistically relevant datasets from literature [*Sassen and Benson*, 2001; *Sassen et al.*, 2000; *Platt et al.*, 1998]. The mean δ' values and the corresponding sample standard deviation for DDU and FLR are shown for 10°C-bin size. It

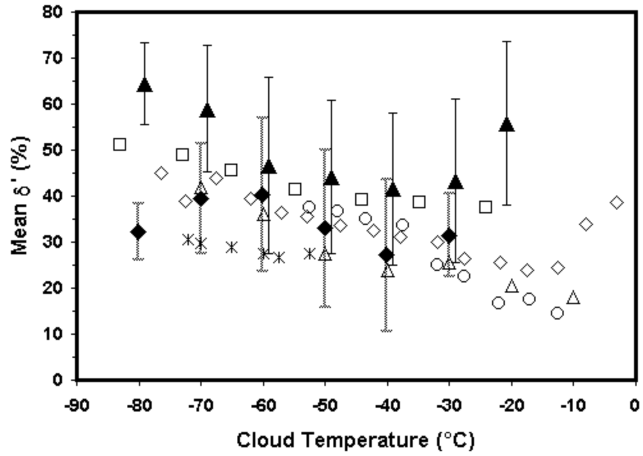

Figure 2. Comparison of δ' values vs. temperature for DDU, FLR, and other geographical locations. Bars show the SD of δ' within each 10°C bin. (Symbols: (✦)DDU, (▲)FLR, (◇)Midlatitude, FARS [*Sassen and Benson*, 2001], (□)Pacific Ocean, TOGA/COARE [*Sassen et al.*, 2000], (Δ)Equatorial Kavieng, (o)Midlatitude Aspendale (Summer), (*)Tropical Darwin [*Platt et al.*, 1998]).

is evident that the FLR depolarization values were larger than the DDU and than most literature values over the whole temperature range. For most temperatures, the DDU data lay in the lower range of data to be found in the literature. A negative trend with temperature similar to those observed in the data of the literature cited was found for DDU. A similar temperature trend, coupled with low depolarization values, was already observed in DDU [*Del Guasta et al.*, 1993] but the latter data were obtained using a different calibration protocol and were thus not directly comparable with the results of this work. FLR cirrus also showed a negative depolarization trend with temperatures in the coldest regions ($T < -40°C$). The positive trend of δ' with temperature in warmer FLR cirrus was perhaps due to the limited number of cirrus observations available in this temperature range.

3.2. Analysis of In-Cloud Depolarization Variability

[12] Each cloud event was characterized by a value of ε. For testing the robustness of ε as an indicator of depolarization variability, the time-height-depolarization color plots of each cloud were used to visually classify the cloud measurements roughly into two classes:

[13] 1) "uniform cloud" (no evidence of structures with contrasting depolarization)

[14] 2) "mixed phase or non-uniform cloud" (evidence of structures with contrasting depolarization) ε was calculated automatically for each cloud and the numerical results were compared with the visual classification. We found that 95% of DDU "uniform" clouds had $\varepsilon < 0.22$, while 88% of "non-uniform" clouds showed higher ε values. In FLR, "uniform" clouds were unusual but all of them showed $\varepsilon < 0.45$. Some FLR data of lower quality (noisy) were also included in this work: 80% of them showed $\varepsilon > 0.72$.

[15] The histogram of ε values for DDU and FLR is shown in Figure 3. The different median values of the two datasets could not be explained as a result of different measurement conditions or different noise levels. The in-cloud depolarization of DDU clouds was found to be statistically more uniform than that of FLR, with a median $\bar{\varepsilon} = 0.2$, corresponding to a ±20% in-cloud variability of δ. As δ is typically 20–40% in DDU, the absolute in-cloud variability was typically ±4–8%. This result converges with the visual classification of the data, in which 43% of the DDU cloud events were classified as "uniform". In FLR, a ±60% variability of in-cloud δ was, instead, common, since $\bar{\varepsilon} = 0.62$. Data of lower quality or affected by noise occupied the right tail of the FLR distribution ($\varepsilon > 0.7$) having values that were rarely present in the corresponding DDU histogram.

[16] The depolarization-variability indicator ε was also calculated for the DDU and FLR ($\beta_p - \beta_s$) scatter plots collecting all the cirrus events of each dataset. The resulting two values, ε'_{DDU} and ε'_{FLR}, have the significance of depolarization variability within the whole dataset (Figure 3). ε'_{DDU} and ε'_{FLR} were much greater than the median of ε values calculated within each dataset. This result suggested that the different cirrus events within each dataset could not be considered as subsets of a single ($\beta_p - \beta_s$) distribution, but in fact represented optically-distinct clouds. This idea was numerically confirmed by the statistical test of significance applied to the δ regression coefficients [*Edwards*, 1984]. We tested the null hypothesis that assumes that all the δ values within each data set are in fact equal, and that differences in observed δ values are just a result of random sampling and noise. The Fisher-test was $F = 7078$ for DDU ($df = 50$) and $F = 1380$ for FLR ($df = 33$). Both these values lead to a significance level $p < 0.000001$, that permits the rejection of the null hypothesis. This means that the cirrus studied in each of the two datasets could not be considered as random samplings of two "big clouds" but have their own individuality.

3.3. Temperature Trend of ε

[17] As temperature is the main physical factor influencing the ice crystal habit in the unperturbed atmosphere, a possible trend of ε with temperature was searched. Figure 4

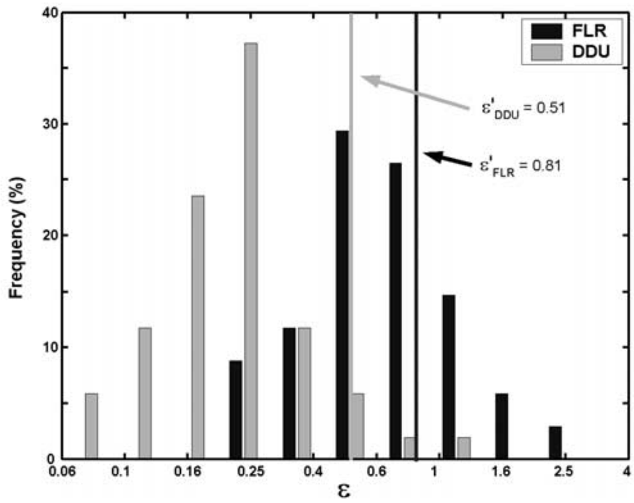

Figure 3. Histogram of ε for the 34 FLR and the 51 DDU cirrus events. ε'_{DDU} and ε'_{FLR} were computed for the whole dataset.

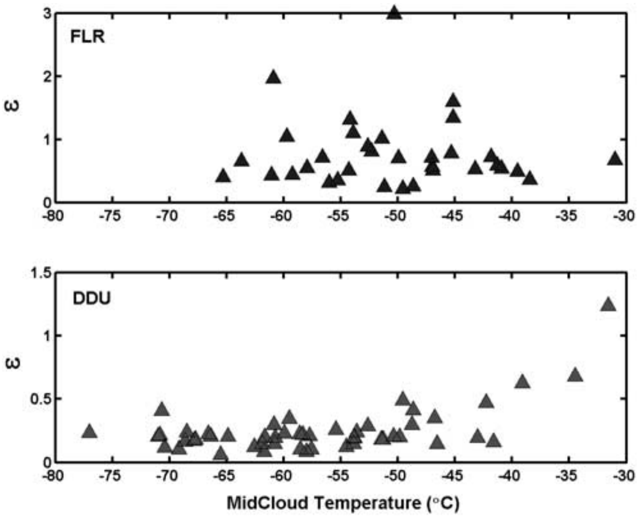

Figure 4. Temperature trend of ε for the FLR and DDU datasets.

shows the trend of ε for FLR and DDU with midcloud temperature. DDU data showed a relative constancy of ε with temperatures in the (−80, −50°C) range, while larger ε values were observed at higher temperatures, where the presence of supercooled water droplets was probable. A wide dispersion of DDU depolarization data above −30°C, similarly explained, was already pointed out by *Del Guasta et al.* [1993]. FLR data showed a wide in-cloud depolarization variability throughout the (−65, −30°C) temperature range, without any evident trend (Figure 4).

4. Conclusions

[18] A significant difference between polar and midlatitude cirrus depolarization, observed by means of two very similar LIDAR systems, was pointed out. The difference was not simply limited to different mean depolarization values (polar cirrus showed a markedly lower mean depolarization than that of midlatitude clouds), but was extended to the in-cloud variability of depolarization values. DDU clouds were markedly more uniform than FLR ones in terms of depolarization in the (−80, −50°C) range. Microphysical or dynamical differences between the two sites should be invoked in order to explain the differences observed. Midlatitude cirrus are often more turbulent than those found in the calm polar atmosphere. Another possible difference lies on the presence of a busy air corridor above Florence, as contrails are often observed before and during the occurrence of cirrus layers. For this reason, most of the FLR cirrus measurements are "polluted" (or are caused) by contrails. The microphysics of the FLR upper troposphere is thus highly perturbed when compared with the relatively clean and dynamically stable upper air of the Antarctic. This hypothesis could be tested by other LIDAR observers located at midlatitudes: The use of any indicator of depolarization variability such as ε (which is virtually insensitive to miscalibrations of the two polarized reception channels and to the duration of the measurement) could be useful in order to compare the cirrus depolarization obtained in very different locations and with different measurement conditions.

[19] **Acknowledgments.** One of the authors (EV) undertook this work with the support of the "ICTP Programme for Training and Research in Italian Laboratories, Trieste, Italy". The other author (MDG) acknowledges the support of the Italian Space Agency (ASI, contract I/R/188/02) and of the "Programma Nazionale di Ricerche in Antartide" (PNRA).

References

Del Guasta, M., Simulation of LIDAR returns from pristine and deformed hexagonal ice prisms in cold cirrus by means of "face tracing", *J. Geophys. Res.*, *106*(D12), 12,589–12,602, 2001.

Del Guasta, M., and K. Niranjan, Observation of low-depolarization contrails at Florence (Italy) using a 532–1064 nm polarization LIDAR, *Geophys. Res. Lett.*, *28*(21), 4067–4070, 2001.

Del Guasta, M., M. Morandi, L. Stefanutti, J. Brechet, and J. Piquad, One year of cloud LIDAR data from Dumont d'Urville (Antarctica) 1. General overview of geometrical and optical properties, *J. Geophys. Res.*, *98*(D10), 18,575–18,587, 1993.

Edwards, A. L., *An introduction to linear regression and correlation*, W. H. Freeman and Company, New York, p. 206, 1984.

Morandi, M., A complete procedure for inverting backscattering LIDAR returns, *Res. Rep. RR/GCF/92. 11*, Ist. di Ric. Onde Ellettromagn., 1992.

Platt, C. M. R., S. Young, P. Manson, G. Patterson, S. Marsden, R. Austin, and J. Churnside, The optical properties of equatorial cirrus from observations in the ARM Pilot Radiation Observation Experiment, *J. Atmos. Sci.*, *55*, 1977–1996, 1998.

Sassen, K., The polarization LIDAR technique for cloud research: A review and current assessment, *Bull. Am. Meteorol. Soc.*, *72*(12), 1848–1866, 1991.

Sassen, K., and S. Benson, A midlatitude cirrus cloud climatology from the Facility for Atmospheric Remote Sensing. Part II: Microphysical properties derived from LIDAR depolarization, *J. Atmos. Sci.*, *58*, 2103–2112, 2001.

Sassen, K., R. Benson, and J. Spinhirne, Tropical cirrus cloud properties derived from TOGA/COARE airborne polarization LIDAR, *Geophys. Res. Lett.*, *27*(5), 673–676, 2000.

Stefanutti, L., F. Castagnoli, M. Del Guasta, M. Morandi, V. M. Sacco, L. Zuccagnoli, S. Godin, G. Megie, and J. Porteneuve, The Antarctic ozone LIDAR system, *Appl. Phys. B*, *55*, 3–12, 1992a.

Stefanutti, L., F. Castagnoli, M. Del Guasta, M. Morandi, V. M. Sacco, V. Venturi, L. Zuccagnoli, J. Kolenda, H. Kneipp, P. Rairoux, B. Stein, D. Weidauer, and J. P. Wolf, A four-wavelength depolarization LIDAR for polar stratospheric cloud monitoring, *Appl. Phys. B*, *55*, 13–17, 1992b.

Sun, Y., Z. Li, and J. Bösenberg, Depolarization of polarized light caused by high altitude clouds. 1: Depolarization of LIDAR induced by cirrus, *Appl. Opt.*, *28*(17), 3625–3632, 1989.

M. Del Guasta, Istituto di Fisica Applicata "Nello Carrara" (IFAC) CNR, Via Panciatichi 64 50127, Florence, Italy. (M.DelGuasta@ifac.cnr.it)

E. Vallar, Physics Department, De La Salle Univ., 2401 Taft Avenue, 1004, Manila, Philippines. (vallare@dlsu.edu.ph)