Extinction coefficients from lidar observations in ice clouds compared to in-situ measurements from the Cloud Integrated Nephelometer during CRYSTAL-FACE

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Abstract

This paper presents a comparison of volume extinction coefficients in tropical ice clouds retrieved from two instruments : the 532-nm *Cloud Physics Lidar* (CPL), and the in-situ probe *Cloud Integrating Nephelometer* (CIN). Both instruments were mounted on airborne plaftorms during the CRYSTAL-FACE campaign and took measurements in ice clouds up to 17km. Coincident observations from three cloud cases are compared : one synoptically-generated cirrus cloud of low optical depth, and two ice clouds located on top of convective systems. Emphasis is put on the vertical variability of the extinction coefficient. Results show small differences on small spatial scales (~100m) in retrievals from both instruments. Lidar retrievals also show higher extinction coefficients in the synoptic cirrus case, while the opposite tendancy is observed in convective cloud systems. These differences are generally variations around the average profile given by the CPL though, and general trends on larger spatial scales are usually well reproduced. A good agreement exists between the two instruments, with an average difference of less than 16% on optical depth retrievals.

1. Introduction

Cirrus clouds are high altitude clouds mostly composed of ice crystals. Since they consistently cover more than 30% of the earth's surface (Wylie et al., 1994), their influence on the radiation budget cannot be overlooked (Stephens et al., 1990). The radiative influence of a given cirrus cloud depends mostly on the delicate balance between its albedo effect and its greenhouse effect. The dominant effect is globally unknown, and locally it depends on the microphysical and optical properties of the considered cirrus cloud. Most noticeably, the quantity of reflected sunlight reflected by a cirrus cloud (and thus its albedo effect) is directly tied to its optical thickness. The optical thickness τ of a cloud layer is defined as $\tau = \int_{z_0}^{z_1} \alpha(z) dz$: the vertical integration of its extinction coefficient $\alpha(z)$ between the layer boundaries z_0 and z_1. The albedo effect of a cloud is thus directly dependent on its vertical profile of extinction coefficient. A good knowledge of extinction coefficient profiles, and thus optical depth, in cirrus clouds would lead to a better estimation of their general albedo effect. Due to the high altitude of cirrus clouds, direct *in situ* measurement of their microphysical properties is a difficult task that cannot be pursued on a systematic basis. Moreover, in the tropical regions ice clouds are often located on top of thick cumulonimbus systems (ref), which means high-altitude observations are a necessity. Because of their large horizontal and vertical extensions, these systems have a large-scale radiative impact on the planet surface and atmosphere (Hartmann et al., 1992), and their creation through fast convection leads to specific microphysic and optical properties (McFarquhar and Heymsfield, 1996 ; Heymsfield and McFarquhar, 1996). Unfortunately, when conducting satellite studies using passive remote sensing it is often difficult to separate the optically thin ice cloud layer from the underlying convective systems, meaning high uncertainties in the retrievals (Chiriaco et al. 2004). This stresses the need for active remote sensing, such as the lidar, whose sensitivity to optically thin clouds makes it one of the most appropriate instruments for cirrus study (Platt,

1973) and can give valuable insights into ice cloud microphysics (Noel et al. 2004, 2004b). Lidar retrievals of extinction coefficients are an effective tool for studying the optical depth of ice clouds out of reach of in-situ observations, and are not subject to passive remote sensing limitations, as the variability of extinction coefficients is observed as a function of penetration inside the cloud layer. Moreover, the upcoming launch of a 532-nm lidar on a spaceborne platform in the framework of the CALIPSO mission (Winker et al. 2003) will lead to retrievals of extinction coefficients and thus optical depths on a global scale, even in tropical ice clouds on top of optically thick convective systems. However, the reliability of these extinction coefficient retrievals needs to be assessed.

The present study compares 3 cases (July 26th, 28th and 29th) of volume extinction coefficients retrieved from observations of tropical ice clouds during the *Cirrus Regional Study of Tropical Anvils and Cirrus Layers– Florida Area Cirrus Experiment* (CRYSTAL-FACE, Jensen et al. 2004). Actual in-situ observations from the airborne collocated probe Cloud Integrating Nephelometer (CIN) are compared with lidar retrievals from the *Cloud Physics Lidar* (CPL). The CRYSTAL-FACE campaign is presented in Sect. 2, along with the instruments used by the present study. The extinction coefficients retrieved from both instruments are then presented are compared in Sect. 3. Results are discussed and conclusion is given in Sect. 4.

2. Volume extinction coefficient retrievals during CRYSTAL-FACE

The CRYSTAL-FACE campaign was held in July 2002 over Florida and the Gulf of Mexico, to provide comprehensive measurements needed to better understand the microphysical and radiative properties and formation processes of ice clouds on top of thick convective cloud systems. Five midaltitude to high-altitude aircraft carried numerous in situ and remote sensing

instruments, with simultaneous ground-based observations.

Among these, the NASA *Cloud Physics Lidar* (CPL), a three-wavelength (355 nm, 532 nm and 1064 nm) backscatter lidar (McGill et al., 2002), was looking downward from the NASA ER-2 aircraft (King and al. 2003) and provided several days of observations from as high as 20 km, with a vertical resolution of 30 m and an horizontal resolution of approximately 200 meters at the typical ER-2 flying speed of 200 m.s^{-1}. The CPL telescope field of view is 100 μradians, so the footprint on a cloud located at less than 10 km (the typical distance during CRYSTAL-FACE) would be less than 1 meter wide. This configuration allowed unique monitoring of ice clouds located on top of tropical convective systems, which would be impossible from the ground because of the lower layers of thick water clouds blocking the lidar penetration. From the raw backscattered laser light measured by the CPL telescope, variables are retrieved for clouds and aerosols, including cloud layer base and top altitudes, optical depth τ, and extinction and depolarization profiles. The technique used to retrieve volume extinction coefficient profiles is explained in McGill et al., 2003, and is based on the standard lidar inversion technique (see e.g. Spinhirne et al., 1980) with a specific treatment for the extinction-to-backscatter ratio : when possible, this ratio is retrieved directly from lidar observations (through a "transmission-loss" technique) ; when this is not possible, the ratio is either provided by external observations, or extracted from look-up tables.

The *Cloud Integrating Nephelometer* (CIN) was mounted on the WB-57 aircraft, that is able to fly through the top of tall convective systems thanks to its high ceiling (up to 18km). The primary objective of the CIN is to measure the asymmetry parameter *g* (Twomey 1977), by using a 635nm laser beam to irradiate airborne particles that scatter light into four sensors, consisting of circular light-diffusing disks and photomultipliers (Gerber et al., 2000). Two of these sensors measure the forward-scattered and backscattered light, while the other two provide the same information weighted by a cosine function. The volume extinction

parameter is then retrieved from the observations of the two first sensors after taking into account the light scattered by diffraction (Eq. 7 in Gerber et al., 2000). The maximum error on the extinction parameter is estimated to $\pm$ 7% in ice clouds ($\pm$ 2.5% when the crystal habits are known).

3. Coincident observations in cirrus clouds

During CRYSTAL-FACE, cirrus clouds were observed during several hours by the CPL (on the ER-2) and the CIN (on the WB-57), but most of the time the observations were not simultaneous. This study will focus on the short periods of time when the two instruments were functioning simultaneously while their two supporting aircraft were flying in the same area, and thus the two instruments were monitoring the same cloud. To evelate the variability of extinction with altitude, and the correlation between results from both instruments, only cases when the WB-57 was either climbing or descending in the cloud layer were considered. Three periods of observation fit this description (July 26th, 28th and 29th) and are described in Table 1.

The July 26th case is one of the rare occurrences of synoptically-generated cirrus clouds observed during a survey flight south to 14 degrees North latitude. The nonconvective cirrus layer detected on that day was more than 1km thick, and was described extensively in e.g. McGill et al, 2004. Lidar observations of extinction coefficient for this case are shown in Fig. 1 as a function of time and altitude, on a logarithmic color scale. For each CPL profile, coordinates of the supporting ER-2 aircraft were compared to those of the WB-57 in the timeframe of coincidence, the maximum delay between both aircraft being 6 minutes. For each CPL profile, extinction coefficients were extracted from the CIN data at the point of closest WB-57 and ER-2 coincidence. The altitude of the WB-57 at these points is shown in Fig. 1 (symbols) for the July 26th case. To sample the maximum of cloud data during descent,

the WB-57 was often spiraling inside cloud systems, which explains why these points are not in chronological order. The WB-57 began its descent at 17.5km around 18:55, from when it went down to 13km in approximately 5 minutes. The extinction coefficients observed by the CIN during this period are shown as symbols in Fig. 2 as a function of altitude, with horizontal bars showing the instrumental uncertainty. The average profile of extinction coefficients retrieved from CPL observations during the same timeframe is shown in full line, the shaded area showing the standard deviation around the average. The agreement between both instruments is good between 13 and 14.2km, even for the relatively low extinction coefficients of this case (generally below 10^{-3} m^{-1}), with an average difference of 0.166 10^{-3} between profiles. Agreement is not as good between 14.2 and 15km, where the lidar retrievals are clearly lower (2 10^{-4} to 4 10^{-4} m^{-1}) than the CIN observations (3 10^{-4} to 6 10^{-4} m^{-1}), which could be due to local variations encountered by the WB-57 during its descent. Integrating both profiles of extinction coefficient (Sect. 1) leads to similar optical depths close to unity (Table 2), with the CPL value 16% higher than the CIN observations. However, the CIN detected particles above the tropopause level (15.5km according to radiosoundings launched from Tampa, 27.70N, 82.40W at 23:00GMT), with very low extinction coefficients between 10^{-4} and 3 10^{-4} m^{-1}, that do not show up in the lidar retrievals (Fig. 2).

The July 28th and 29th cases are more typical of the small-scale convective systems that developed frequently in the tropical area monitored during CRYSTAL-FACE (McGill et al. 2004). Such systems extended horizontally over 100 km, and often went up to the tropopause, meaning their higher layers were often composed of ice crystals over several kilometers. CPL profiles of extinction coefficients are shown in Fig. 3a (July 28th) and 3b (July 29th), with the WB-57 altitude at coincident points in symbols. On July 28th, the WB-57 went from 16km at 22:45 down to 13.5km around 23:00 ; on July 29th it went from 14km at 20:00 down to 12.5km at 20:12. The extinction coefficient profiles measured by the CIN during these

descents are shown as symbols in Fig. 4a (July 28th) and 4b (July 29th), with the average CPL retrievals during the same timeframe in full line and standard deviation shown as a shaded area. The sudden break in lidar retrievals after a few thousand meters (made obvious by the vertical structures of Fig. 3b) can be explained by the total extinction of lidar signal, due to the high optical depth of the probed convective systems. The in-cloud, small-scale variations in extinction coefficients are not always similar in observations from both instruments (e.g. Fig. 4B between 12.7 and 13.2 km), however the overall agreement is good, and the retrieved optical depths are in the same ranges (Table 2), with CPL values only 3% (July 29th) and 16% (July 28th) lower.

4. Discussion and conclusion

This study shows a comparison between volume extinction coefficients observed from a CIN in-situ probe and retrievals from lidar backscattered profiles (Sect. 2). Three coincident observation periods are compared, highlighting the variability with altitude (Sect. 3). Results show a very good agreement between both instruments for extinction coefficients sometimes as low as 10^{-4} m^{-1} (Fig. 2). Overall the extinction coefficient profiles retrieved from CPL observations show less small-scale variability (in the 100-meters range) than the CIN observations. This is probably due to the fact that lidar retrievals were averaged during the WB-57 descent in the cloud (that took up to 6 minutes), as the CIN observations are often contained in the standard deviation area of CPL retrievals. These differences are minor though, and as variations on larger scales are well reproduced the retrieved optical depth is only slightly affected (3% to 16% variation between the two instruments). In the two convective system cases, the extinction coefficients retrieved from the lidar were slightly lower than those observed in-situ by the CIN, while the opposite is true in the synoptic cirrus case (Table 2). These differences could be explained by the sensitivity limitations of the lidar

: in the synoptic case (July 26th), the lidar was not able to detect the particles above the tropopause shown in the CIN observations. This can be explained either by a very low concentration of particles that did not produce enough backscattered light, or a very specific spatial distribution of these particles that would hide them from the lidar field of view. In the convective cloud cases (July 28th and 29th), the lidar was only able to penetrate a fraction of the whole ice cloud layer. Overall, the lidar performs reasonably well in such extreme conditions, and as it was shown previously those differences are only significant on small spatial scales and are only a secondary influence on larger scale trends and integrated results. The overall good agreement between results from both instruments strengthens the confidence in extinction coefficients retrieved from lidar observations. Specifically, the good performance of the lidar extinction retrieval at very low values (10^{-4} m^{-1}) confirms its ability to detect and study subvisible cirrus successfully. This is especially important today, as observations from the spaceborne CALIPSO mission(Winker et al. 2003) will soon be available, leading to an extensive mapping of ice cloud optical and microphysical properties.

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Wylie, D. P. and Menzel, W. P. and Woolf, H. M. and Strabala, K. L. 1994 :Four Years of

6. Table captions

Table 1. Properties of each case of collocated observations from the CPL and CIN during

CRYSTAL-FACE.

Table 2 : Cloud optical depth _ obtained from integration of volume coefficient profiles from

t h e   C P L   a n d   C I N   o b s e r v a t i o n s .

	July 26th	*July 28th*	*July 29th*
Time of observation	18:54 – 19:03	22:45 – 23:00	20:01 – 20:12
WB-57 Altitude range	13 – 17 km	13.5 – 16km	12.5 – 14km

Table 1. Properties of each case of collocated observations from the CPL and CIN during

CRYSTAL-FACE.

	July 26th	*July 28th*	*July 29th*
From CPL observations	1.08	1.40	2.09
From CIN observations	0.90	1.67	2.16

Table 2 : Cloud optical depths _ obtained from integration of volume coefficient profiles from the CPL and CIN observations.
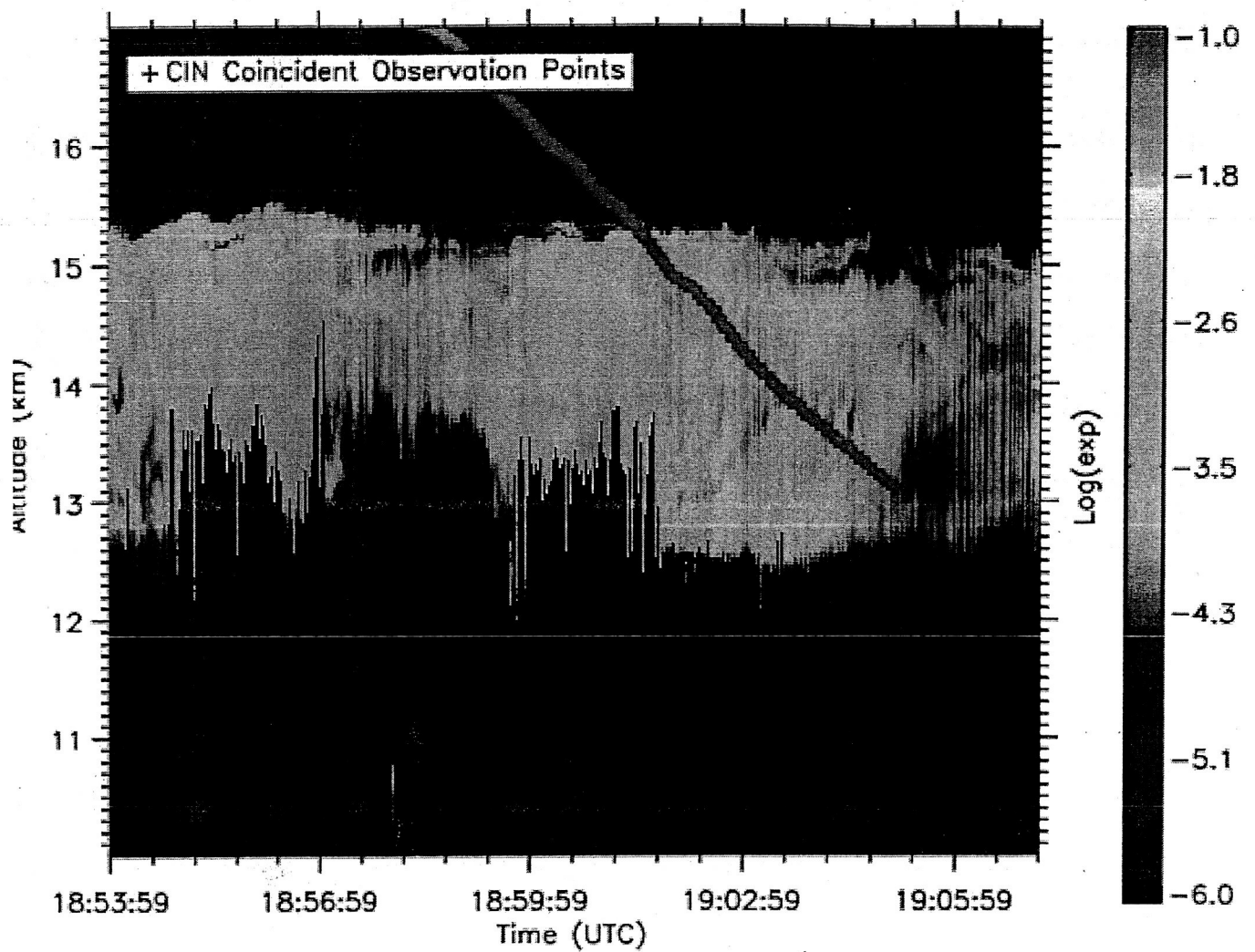
Figure captions

Fig. 1 : Observations of lidar extinction coefficients for the July 26th case on a logarithmic color scale (m^{-1}), 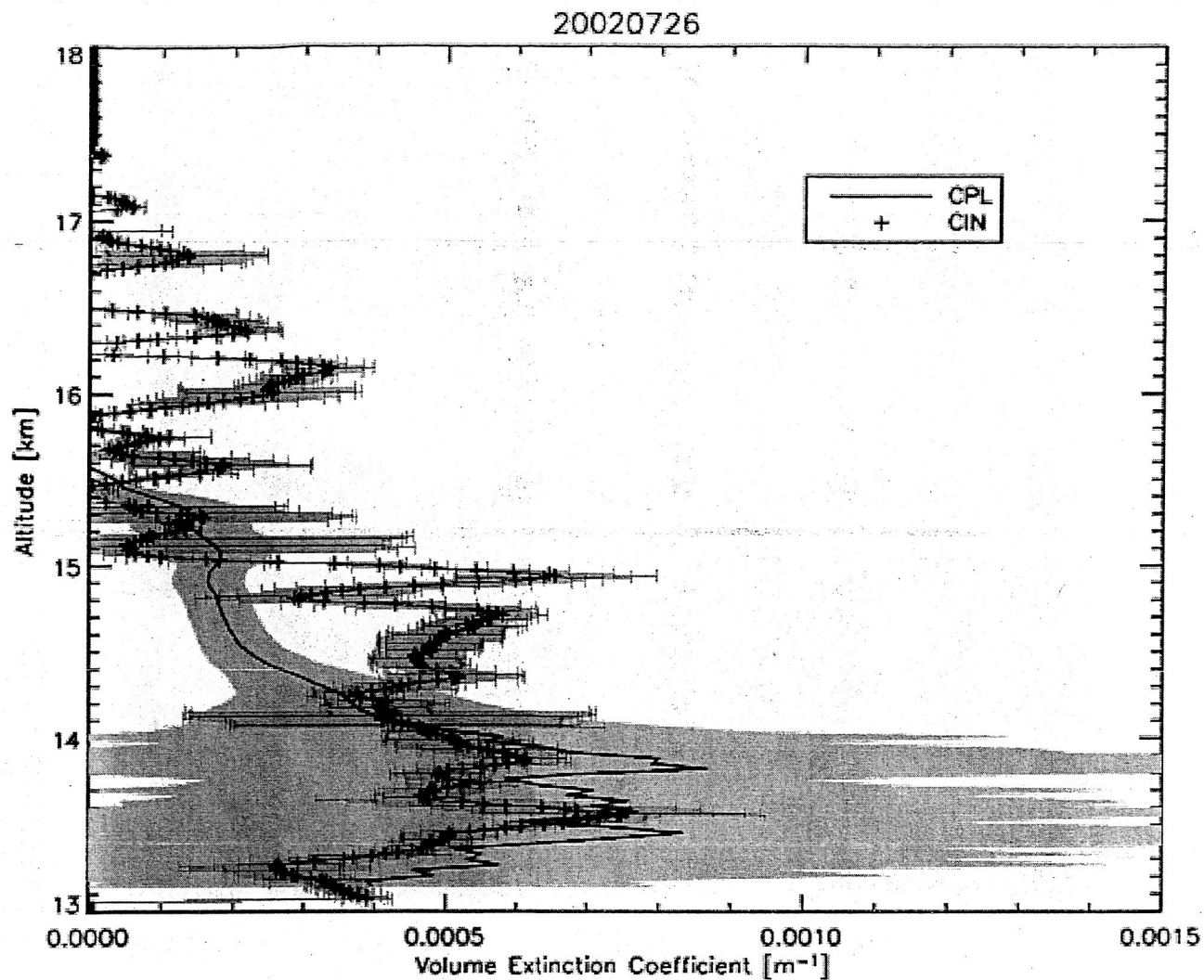with the WB-57 flight path indicated by dots.Fig. 2 : Retrieved profile of volume extinction coefficients (m^{-1}) from CPL observations (average profile in full line, standard deviation in shaded grey) and collocated observations from the CIN probe (crosses, with instrument uncertainty shown as horizontal bars) for the July 26th case, as a function of altitude (km).
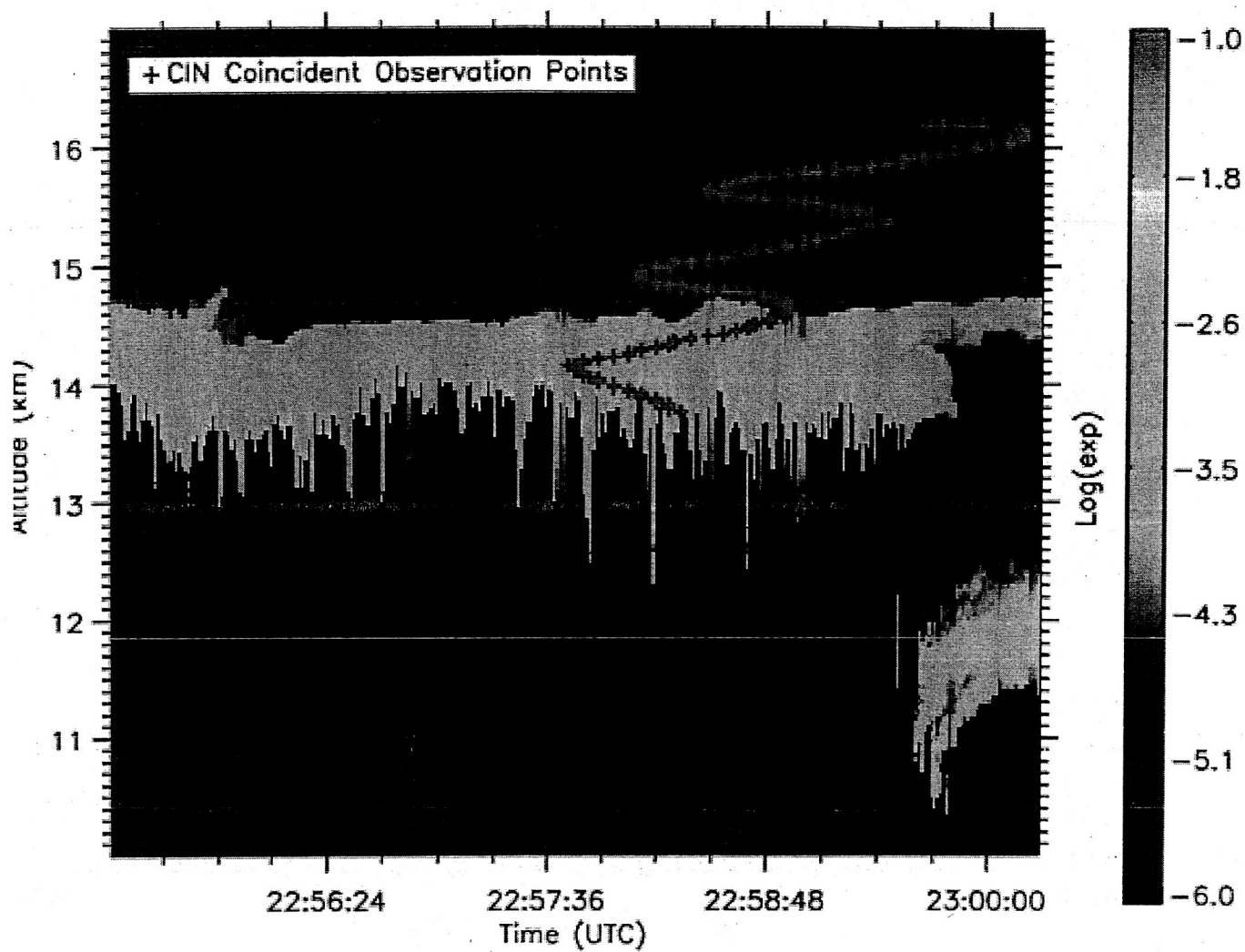
Fig. 3 : (a) same as Fig.1, for the July 28th case. (b) same as Fig. 1, for the July 29th case.

Fig. 4 : (a) same as Fig.2, for the July 28th case. (b) same as Fig. 2, for the July 29th case.

Fig. 1 : Observations of lidar extinction coefficients for the July 26th case on a logarithmic color scale (m^{-1}), with the WB-57 flight path indicated by dots.

Fig. 2 : Retrieved profile of volume extinction coefficients (m⁻¹) from CPL observations (average profile in full line, standard deviation in shaded grey) and collocated observations from the CIN probe (crosses, with instrument uncertainty shown as horizontal bars) for the July 26th case, as a function of altitude (km).

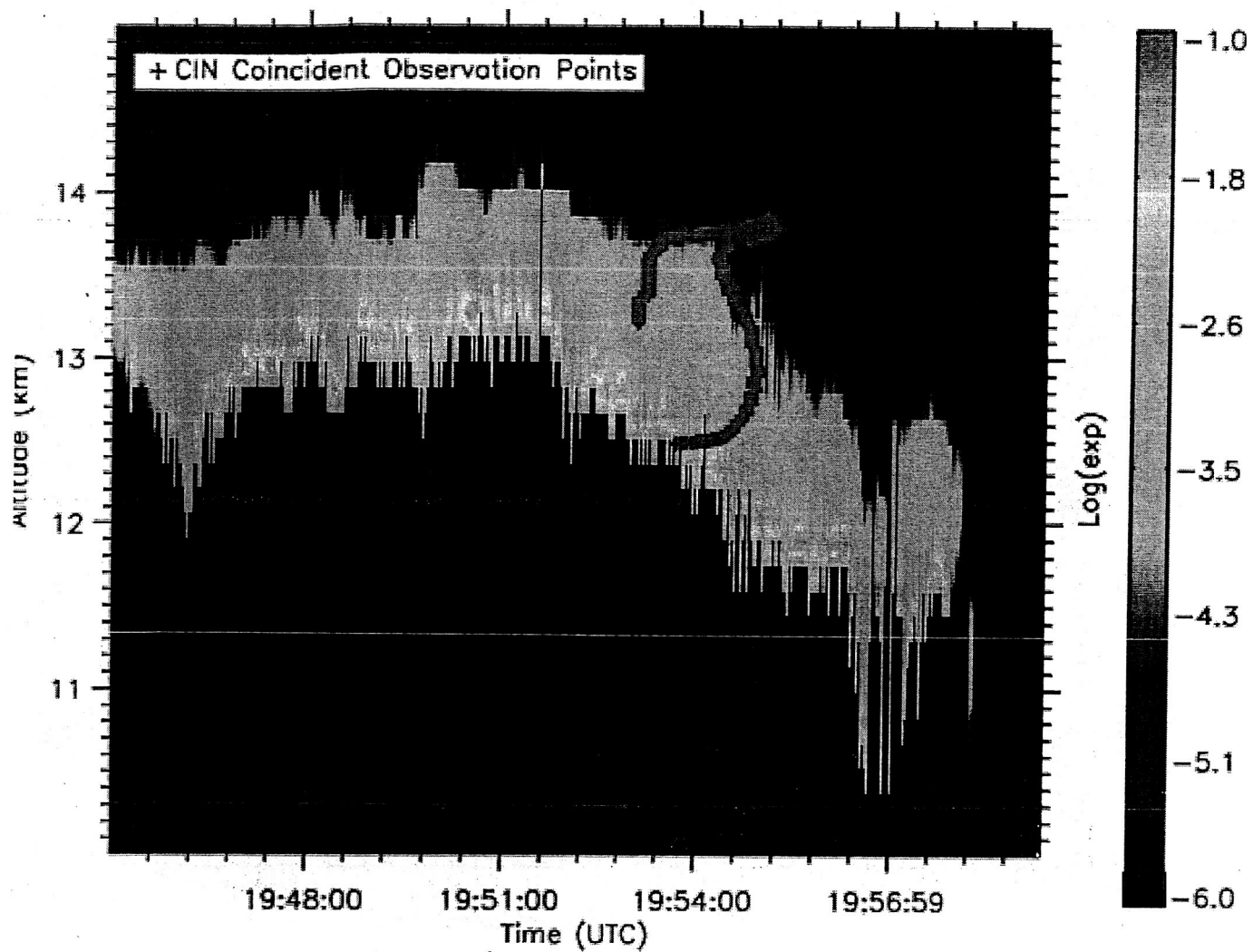Fig. 3A : Same as Fig. 1, for the July 28th case.

Fig. 3B : Same as Fig. 1, for the July 29th case.
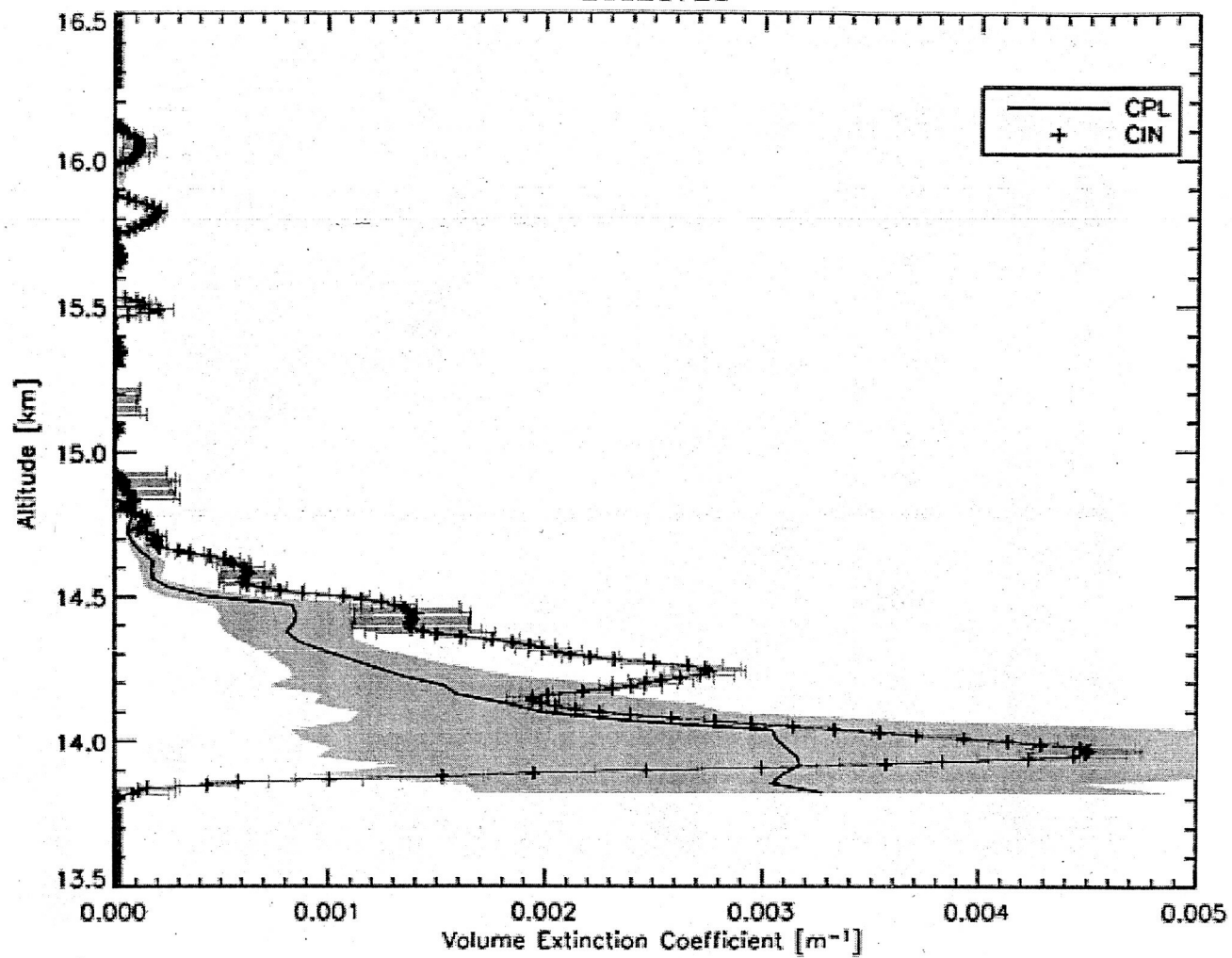
20020728

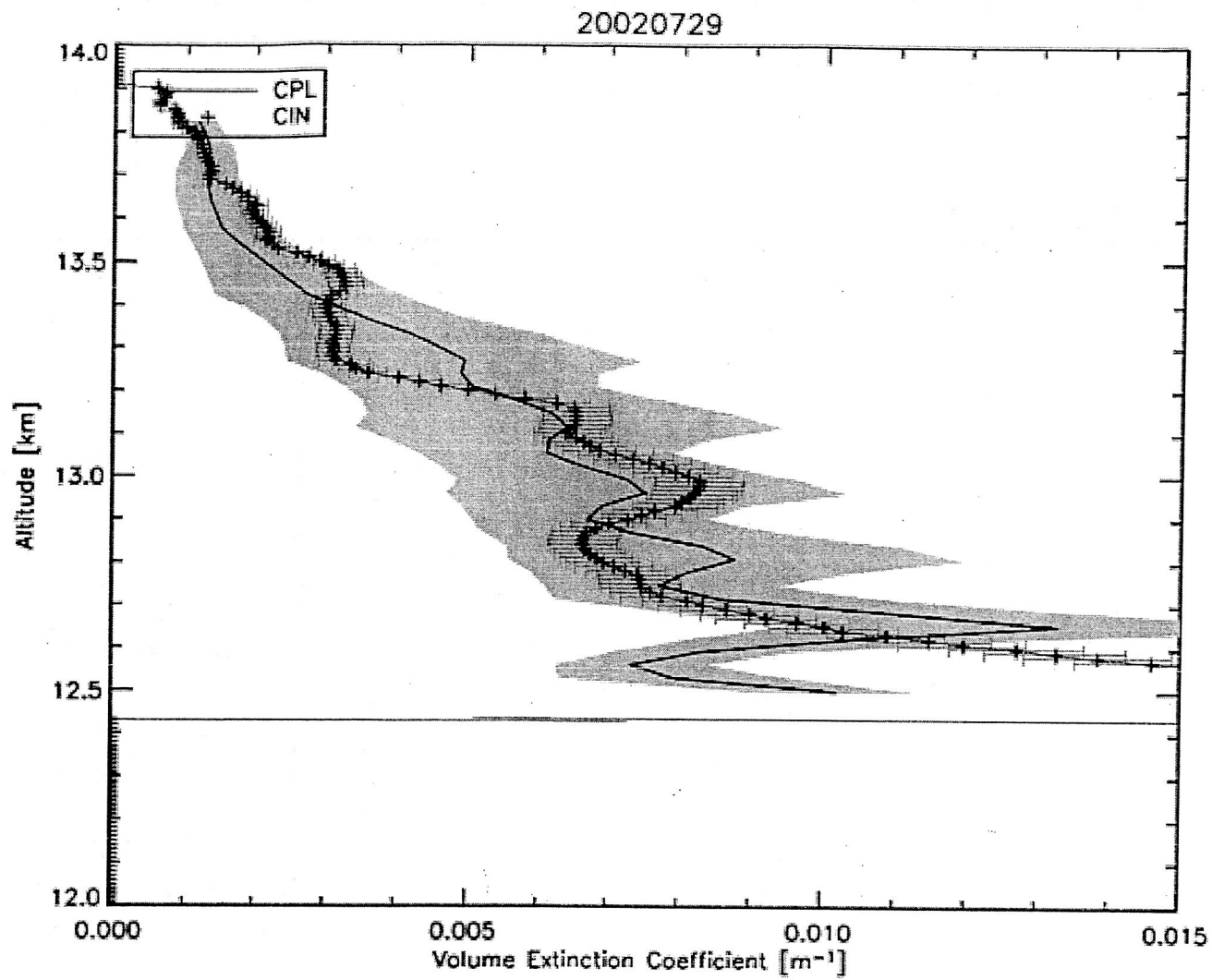Fig. 4A : Same as Fig. 2, for the July 28th case.

Fig. 4B : Same as Fig. 2, for the July 29th case.

This paper presents a comparison of volume extinction coefficients in tropical ice clouds retrieved from two instruments : the 532-nm *Cloud Physics Lidar* (CPL), and the in-situ probe *Cloud Integrating Nephelometer* (CIN). Both instruments were mounted on airborne plaftorms during the CRYSTAL-FACE campaign and took measurements in ice clouds up to 17km. Coincident observations from three cloud cases are compared : one synoptically-generated cirrus cloud of low optical depth, and two ice clouds located on top of convective systems. Emphasis is put on the vertical variability of the extinction coefficient. Results show small differences on small spatial scales (~100m) in retrievals from both instruments. Lidar retrievals also show higher extinction coefficients in the synoptic cirrus case, while the opposite tendancy is observed in convective cloud systems. These differences are generally variations around the average profile given by the CPL though, and general trends on larger spatial scales are usually well reproduced. A good agreement exists between the two instruments, with an average difference of less than 16% on optical depth retrievals.