Cirrus optical properties observed with lidar, radiosonde, and satellite over the tropical Indian Ocean during the aerosol-polluted northeast and clean maritime southwest monsoon

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[1] Cirrus formation and geometrical and optical properties of tropical cirrus as a function of height and temperature are studied on the basis of INDOEX (Indian Ocean Experiment) lidar and radiosonde measurements and satellite observations of deep convection causing the generation of anvil cirrus. Lidar and radiosonde measurements were conducted at Hulule (4.1°N, 73.3°E), Maldives, during four field campaigns carried out in February–March 1999 and March 2000 (northeast (NE) monsoon season, characterized by increased concentrations of anthropogenic aerosols over the Indian Ocean) and in July and October 1999 (southwest (SW) monsoon season, characterized by clean maritime conditions). As a result of a stronger impact of deep convection on cirrus formation during the SW monsoon season, cirrus clouds covered the sky over the lidar site in only 35% (NE), but 64% (SW) of the measurement time. Subvisible cirrus (optical depth \( \leq 0.03 \)), thin (optical depth from 0.03 to 0.3), and opaque cirrus (optical depth \( \geq 0.3 \)) were observed in 18%, 48%, and 34% (NE) and in 8%, 52%, and 40% (SW) out of all cirrus cases, respectively. Mean midcloud heights were rather similar with values of 12.9 ± 1.5 km (NE) and 12.7 ± 1.3 km (SW). In 25% of the cases the cirrus top height was found close to the tropopause. Mean values of the multiple-scattering-corrected cirrus optical depth, cirrus layer mean extinction coefficient, and extinction-to-backscatter ratio were 0.25 ± 0.26 (NE) and 0.34 ± 0.29 (SW), 0.12 ± 0.09 km\(^{-1}\) (NE) and 0.12 ± 0.10 km\(^{-1}\) (SW), and 33 ± 9 sr (NE) and 29 ± 11 sr (SW), respectively. A functional dependency of the extinction coefficient of the tropical cirrus on temperature is presented. All findings are compared with several other cirrus lidar observations in the tropics, subtropics, and at midlatitudes. By contrasting the cirrus optical properties of the different seasons, a potential impact of anthropogenic particles on anvil cirrus optical properties was examined. Differences in the cirrus extinction-to-backscatter ratio suggest that NE monsoon anvil cirrus originating from deep-convection cumulus clouds had more irregularly shaped and thus slightly larger ice crystals than respective SW monsoon anvil cirrus. Because the meteorological conditions were found to vary significantly between the seasons, an unambiguous identification of the influence of Asian haze on cirrus optical properties is not possible.


1. Introduction

[2] Cirrus regularly covers 20% to 35% of the globe [Liou, 1986; Wylie et al., 1994]. In the area of the intertropical convergence zone (ITCZ) this value increases to almost 50% [Wylie et al., 1994]. Tropical cirrus clouds thus have a significant impact on local meteorological processes as well as on the regional to large-scale heat budget of the atmosphere. The radiative impact of ice clouds is complex and is determined by the greenhouse-versus-albedo effect [Liou, 1986; Wylie et al., 1994]. Whereas the scattering of solar radiation causes a net cooling effect for the Earth’s surface, the absorption and emission of infrared radiation leads to a trapping of energy in the Earth-atmosphere system. The way in which these two effects interact and
thus influence the radiation balance of the atmosphere strongly depends on the optical properties, height, thickness, and temperature of the cirrus layers. How cirrus clouds interact with other clouds (i.e., convective clouds), pollution, and large-scale processes, such as changes in the vertical distribution of radiative heating [Stephens, 2002] or sea surface temperature [Ramanathan and Collins, 1991], is not yet completely understood.

Several field campaigns have been carried out in various regions of the globe to improve the knowledge of cirrus cloud occurrence, formation processes, and the climate impact of cirrus clouds. However, especially in the tropics vertically and temporally resolved measurements of cirrus cloud properties are still scarce. Recent studies have focused on the western Pacific warm pool [Platt et al., 1998, 2002; Heymsfield et al., 1998; Sassen et al., 2000; Comstock et al., 2002]. Other lidar statistics of cirrus cloud properties in the tropics are available only for the Seychelles [Pace et al., 2003] and eastern India [Sunilkumar and Parameswaran, 2005].

This contribution presents the most comprehensive lidar- and radiosonde-based cirrus cloud statistics for the region of the tropical Indian Ocean. In the scope of the Indian Ocean Experiment (INDOEX), our six-wavelength aerosol lidar [Althausen et al., 2000] performed more than 500 hours of aerosol and cloud observations. About 250 radiosondes were launched. The primary goal of INDOEX was the characterization of anthropogenic aerosol pollution (Asian haze) advected from south and Southeast Asia in the lower troposphere during the northeast monsoon season [Franke et al., 2003; Müller et al., 2003]. Four field campaigns were carried out in February–March 1999, July 1999, October 1999, and March 2000 so that the underlying data set covers two seasons of the dry northeast (NE) monsoon (February–March 1999, March 2000) as well as one season of the rainy southwest (SW) monsoon (July and October 1999) [Müller et al., 2001]. The cirrus analysis presented here is based on the elastic-backscatter signal profiles measured at 532-nm wavelength.

In a recent publication [Chylek et al., 2006] the possible influence of lower tropospheric pollution on the optical properties of cirrus clouds over the Indian Ocean was discussed. Seas adjacent to the Indian subcontinent are ideal target areas to study the anthropogenic impact on atmospheric processes because the monsoon climate in this region permits contrasting polluted (NE monsoon, January to April) and clean, maritime conditions (SW monsoon, May to October). Chylek et al. [2006] note that MODIS data indicate larger ice crystals in January (2001–2005) and smaller ice crystals in September (2002–2004), corresponding to times of increased pollution and cleaner conditions, respectively. Massie et al. [2007] calculated cirrus reflectivity values determined from the analyses of MODIS radiances during January–March of 2003–2005. No indication of an aerosol influence, e.g., an increase of the cirrus reflectivity with increasing aerosol optical depth, was found. In section 4, this aspect is further discussed on the basis of our lidar-derived values of the cirrus layer mean extinction coefficient and extinction-to-backscatter ratio.

The paper is organized as follows. In section 2, the experimental setup and data analysis methods are described. Section 3 presents the cirrus formation processes are discussed and geometrical and optical properties of the observed cirrus layers are presented and compared with other tropical as well as subtropical and midlatitude cirrus studies. In section 4, the potential impact of anthropogenic pollution on cirrus cloud optical properties is discussed. Section 5 provides a short summary.

2. Experiments

2.1. Lidar

A six-wavelength lidar [Althausen et al., 2000] was employed to measure aerosol and cloud distributions over the Maldives in the framework of INDOEX. The field site was at the Maldives International Airport at Hulule island (4.1°N, 73.3°E). The lidar was optimized for measurements of Asian haze in the height range from 500–5000 m. As a consequence, the Raman channels for particle extinction profiling at 355 and 532 nm could not be used to measure light scattering coefficients in clouds from 10–17 km height. The Raman signals from these heights were too weak, too noisy. Nevertheless, the 532-nm elastic-backscatter channel was powerful enough to cover the range from 500–25000 m and thus to profile cirrus and Rayleigh scattering up to stratospheric heights. The lidar was operated at a fixed off zenith angle of typically 5° or, in several cases, of 30° to avoid the unwanted impact of specular reflection by falling, horizontally oriented ice crystals.

The geometrical properties of ice cloud layers were directly determined from the range-corrected signals, clearly indicating the ice cloud layers as shown in Figure 1. Note, in addition, the aerosol pollution layers in the lower troposphere during the NE monsoon season (Figures 1a and 1c). In cases of inhomogeneous cloud structures (see Figure 1b), we calculated cloud top and base heights for 10-min periods and used the respective mean cloud top and base heights (for the entire observational period) to calculate the mean cirrus layer depth and midcloud temperature from the respective radiosonde data for this individual observation. We interpreted cirrus layers as different ice clouds if they were separated by ≥800 m. In the statistics presented in the next section, only clouds above 9-km height are considered to avoid a possible impact of water clouds on our statistics.

For each cirrus observation lasting from a few minutes to several hours we selected a representative period of typically 5–30 min to determine the optical properties such as the optical depth and column extinction-to-backscatter ratio of the cirrus layer. The column extinction-to-backscatter or column lidar ratio is the ratio of the cirrus optical depth to the backscatter coefficient (180° scattering coefficient) integrated over the cirrus layer and can be interpreted as the cirrus layer mean lidar ratio. Before computing the optical properties we smoothed the temporally averaged lidar signal profiles recorded with 15–60 m vertical resolution with a 120-m vertical smoothing window length to reduce the influence of signal noise.

The so-called forward integration method of the Fernald method [Fernald, 1984] is applied to retrieve the cirrus optical depth and the cirrus lidar ratio. The method is well known in the lidar community and well tested by comparing the results obtained with the Fernald method and from simultaneously conducted Raman lidar observations of
In the Fernald retrieval, the column lidar ratio of the cirrus layer is an input parameter. By applying the forward integration method, pure Rayleigh backscattering below the cirrus is assumed. The most appropriate profile of the cirrus backscatter coefficient is obtained by varying the cirrus lidar ratio until the particle backscatter coefficient above the cirrus layer approaches zero again and varies around zero in the stratosphere because of signal noise. We checked the optimum solution by applying the backward integration method in addition. In this retrieval the computation is started from above the cirrus. In the case of the most appropriate cirrus lidar ratio, the forward and backward integration solutions coincide as illustrated by Ansmann et al. [1992]. This technique is simple and straightforward, and allowed us to accurately determine the apparent (laser-light-attenuation-related) cirrus optical depth, the cirrus layer mean extinction coefficient, i.e., the ratio of the optical depth to the geometrical depth, and of the cirrus lidar ratio. The uncertainty in the retrieval products caused by the assumption of particle free air below and above the cirrus is <10%.

The technique could, however, only be applied in cases with apparent cirrus optical depths from about 0.03 – 0.05 to 0.6. The apparent optical depth is the directly retrieved value without applying any multiple-scattering correction. In cases with almost subvisible cirrus the Fernald retrieval was insensitive to the lidar ratio estimate (25% out of all cirrus cases). All trial values for the cirrus lidar ratio from 1 – 60 sr or even higher values produced almost the same backscatter coefficient profile. In these cases we used an apparent cirrus lidar ratio of 20 sr. This value of 20 sr represents the mean of all retrieved INDOEX cirrus lidar ratios for thin cirrus with optical depth <0.1. An uncertainty of the optical depth of 30% – 50% remains when keeping in mind that the apparent cirrus lidar ratio can easily vary between 10 and 30 sr as a function of particle shape and size [Reichardt et al., 2002].

In cases with thick cirrus with high optical depth >0.6 (6% out of all cases), Rayleigh backscattering above the ice cloud was hard to detect. The signal profiles became very noisy. Supported by several INDOEX Raman lidar observations in optically thick cirrus below 12 km height, it was found that the most appropriate cirrus lidar ratio is close to the one for which the backscatter coefficient solution becomes unstable [Seifert, 2006]. In this study we thus selected that apparent lidar ratio as the most appropriate one that produced the first stable solution when decreasing the apparent lidar ratio stepwise by 1 sr, starting with 25 sr that always produced unstable solutions. This lidar ratio was then applied to the obtained backscatter coefficient profile to estimate the apparent cirrus optical depth. Note, that in all of the analyzed optically thick cirrus cases the first stable solution showed already backscatter values around zero at the top of the cirrus and above the cloud layer. The uncertainty in the retrieval products (apparent column lidar ratio, optical depth, mean extinction coefficient) of optically thick ice clouds is estimated to be 25% as the Raman lidar comparisons indicate.

The receiver field of view of the INDOEX lidar is 0.8 mrad and thus the results are considerably influenced by multiple scattering. This effect is caused by strong forward scattering of laser light in the cirrus and leads to a signif-

![Figure 1](https://example.com/figure1.png)
icant underestimation of the cirrus optical depth by 20%–50%. The apparent values of the optical depth, layer mean extinction coefficient, and lidar ratio are a factor of 1.2–2 lower than the desired, single-scattering-related values. The strength of this underestimation depends on cloud height, cloud depth, strength of light scattering (scattering coefficient), size of the scatterers, laser beam divergence, and the receiver field of view of the lidar [Platt, 1981; Wandinger, 1998; Comstock and Sassen, 2001]. We applied the model provided by Hogan [2006] to determine the multiple scattering effect for each of the observed INDOEX cirrus cases. The model was explicitly developed for cirrus observations with ground-based and spaceborne lidars. Input parameters are the observed cloud height, depth, and the profile of the cloud extinction coefficient that corresponds to the retrieved backscatter coefficient profile multiplied by a single-scattering-related column lidar ratio. Information about the effective, i.e., the cross-section-weighted mean, radius of the hexagonal ice particles needed in the model calculations was taken from Wang and Sassen [2002] who used lidar and radar measurements to determine the ice particle size as a function of temperature. The effective radius decreased from 70 μm at −30°C to 35 μm at −70°C. Temperature profile information for each cirrus case was determined from radiosonde data. Scattering phase functions for hexagonal ice crystals are implemented in the model. The selection of the appropriate scattering phase function depends on the chosen effective radius.

[15] On the basis of the calculated profiles of the totally backscattered laser photons detected with the lidar and the corresponding single-scattering-related lidar signal profiles, we corrected the multiple scattering effect following the scheme of Platt [1981]. The correction procedure is described in detail by Wandinger [1998].

[16] For a given field of view of the receiver telescope the strength of multiple scattering primarily depends on the cloud effective particle size, cloud geometrical depth and the penetration depth of the laser beam into the cloud. When the laser beam hits the cirrus cloud base, almost 50% of the laser light are scattered in the forward direction and remain in the field of view of the receiver telescope. With increasing penetration depth into the cloud the forward scattered light is scattered out of the receiver field of view. Thus the multiple scattering factor $\eta_{ms}$ increases with penetration depth into the cloud, almost independent of its optical depth. $\eta_{ms}$ is defined as the ratio of the observed, apparent optical depth to the single-scattering-related optical depth. The values of $\eta_{ms}$ accumulated around 0.55–0.6 for geometrical depths ≤1 km and mostly ranged from 0.6–0.8 for larger geometrical depths. The impact of multiple scattering is thus largest for geometrically thin, subvisible cirrus as expected [Wandinger, 1998]. The optical depth of subvisible cirrus is underestimated by almost a factor of two. This is in contradiction to other multiple scattering parameterizations. Sassen and Comstock [2001] assumed $\eta_{ms} = 0.9$ for subvisible and optically thin cirrus, 0.8 for relatively thick cirrus, and 0.6–0.7 for optically thick cirrus. With 1 mrad the receiver field of view was similar to the receiver field of view of the INDOEX lidar of 0.8 mrad. Chen et al. [2002] used $\eta_{ms}$ of 0.98–1 for subvisible cirrus, 0.86–0.98 for thin cirrus (optical depth from 0.03–0.3), and 0.58–0.86 for opaque cirrus (optical depth from 0.3–1). Their multiple scattering factor $\eta_{ms}$ is a simple function of the cirrus optical depth $\tau$ [$\eta_{ms} \approx \exp(-\tau)$] and thus approaches 1 for subvisible cirrus with $\tau \rightarrow 0$.

[17] The uncertainty in the optical depth and column lidar ratio introduced by the multiple scattering correction is estimated to be 10% because of the unknown effective size of the ice crystals in each of the observed clouds. This value is estimated from the simulations with different effective particle sizes. Considering all uncertainties, the determination of the cirrus optical properties as shown in the next section was possible with a relative error of about 30%–50%, 15%–20%, and 30% for cases with an apparent cirrus optical depth of <0.04, 0.04–0.6, and >0.6, respectively.

2.2. Radiosonde Observations

[18] During the four field campaigns 250 radiosondes of the type Vaisala RS-80 were launched to provide vertical profiles of pressure, temperature, and humidity up to 20–25 km height. The radiosondes were released at the lidar field site at Hulule. A sonde observation was made during each of the one to six-hour lidar measurement sessions.

2.3. Satellite Observations

[19] NOAA satellites provide an outgoing longwave radiation (OLR) product for the top of the atmosphere. The OLR data are calculated on a daily basis by the Climate Diagnostic Center (CDC), a division of NOAA [Liebmann and Smith, 1996]. The horizontal resolution is 2.5° × 2.5°. Missing values are computed by applying spatial and temporal interpolation. OLR emitted by high, cold, deep convective clouds is much lower than the OLR emitted by warmer low clouds or the surface. Usually, values of less than 170 W/m² indicate deep convection. Deep convection, in turn, indicates regions with extensive lifting of air that may play a role as source regions for cirrus clouds.

3. Results

[20] During the four measurement campaigns in February and March 1999, July 1999, October 1999, and March 2000 regular observations were made each morning, noon, and evening on 93 days. These routine measurements lasted typically one to two hours. Additionally, 57 nighttime measurements were made. Most observations were performed in February and March 1999 during the intensive field phase of INDOEX. Together with the data of March 2000, 106 cirrus cases were counted during the NE monsoon season. 73 cirrus cases were sampled during the SW monsoon season. The sky over the lidar site was covered with cirrus during 43% of the observational time (35% during the NE monsoon, 64% during the SW monsoon). Several observational periods (about 30% of the total record) with thick altocumulus that prevented cirrus observations in October 1999 were excluded from this statistics. During the other three field campaigns, screening by lower tropospheric and midtropospheric cloud layers was a negligible issue.

3.1. Cirrus Formation Processes

[21] According to the current understanding, the primary formation mechanisms of cirrus clouds in the tropics are outflow from deep convection, large-scale uplift of humid
layers, and cooling due to wave activity in the upper troposphere [Jensen et al., 1996]. Convective cumulonimbus clouds are the primary source for outflow cirrus which forms when upper tropospheric winds blow ice particles away from their convective cores. This cirrus is usually denoted anvil cirrus. Also, the anvil clouds that remain in the troposphere after the deep convective cloud dissipated are counted as outflow cirrus. Such cirrus clouds appear as rather opaque, textured clouds with irregular boundaries. They generally persist for 0.5 to 3 days. Their top heights are restricted to the maximum altitude deep convection can reach. Except for a small fraction of less than 1.8%, the upper boundary for deep convection is 14 km [Liu and Zipser, 2005].

[22] Large-scale dynamic lifting of humid layers supports the formation of cirrus at higher altitudes. The lifting leads to a cooling of the layer until the air is supersaturated with water vapor and ice nucleation occurs. Jensen et al. [1996] named different processes which can cause dynamic lifting: flow over continental-scale bulges in the tropopause, flow over large-scale convective systems, and lifting above stratusform regions of mesoscale convective systems. Clouds induced by these processes usually appear as rather tenuous, laminar layers of low optical depth spreading homogeneously over large areas. They have a geometrical depth of about 1 km and are located at altitudes above 14 km, often close to the tropopause or strong temperature inversions.

[23] Deep convective clouds are also capable of causing considerable radiative cooling above their anvils. Thin and subvisible cirrus can form above deep convective clouds. These layers are comparable to plexus clouds but more persistent [Hartmann et al., 2001; Garrett et al., 2004, 2006]. After the deep convective clouds dissolved, the “trapped” cirrus remains in the upper troposphere as a layer located above the remnant of the dissipating anvil cloud and the outflow cirrus.

[24] Recent studies reveal a strong link between cirrus clouds and atmospheric waves which cause in situ cooling on a synoptic scale. Massie et al. [2002] note that subvisible cirrus are associated 50% of the time with regions of the tropics, near the tropopause, for which backward trajectories are not associated with deep convection. These observations are consistent with the formation of cirrus that is due to in situ cooling of humid layers. Boehm and Verlinde [2000] found a strong correlation between descending stratospheric Kelvin waves and the occurrence of cirrus. According to their study, negative temperature deviations from the average temperature in the upper troposphere are directly related to the occurrence of cirrus. Information about the mechanism of the stratospheric Kelvin waves is given by Holton [1992]. A similar behavior is found in our INDOEX radiosonde/lidar data set. Figure 2a shows the radiosonde temperature field and Figure 2b the deviation from the average temperature of all 54 measurement days in spring 1999. The red line in both figures indicates the lapse rate tropopause. The lapse rate tropopause, also referred to as the WMO tropopause, is defined as the lowest level at which the lapse rate decreases to 2 K/km or less, and the average lapse rate from this level to any level within the next higher 2 km does not exceed 2 K/km [Krishna Murthy et al., 1986]. The white line served minimum temperature (cold-point tropopause) of each radiosonde ascent. The black dots at an altitude of 6 km show when the lidar was operated. White vertical lines correspond to observed cirrus clouds. The red areas in Figure 2b correspond to a positive deviation of 5 K and the dark areas to a negative deviation of 5 K from the average temperature. Between Julian day 70 and 85 a cold perturbation can be found at an altitude of about 15 km. During this time period the highest frequency of cirrus clouds was observed. During warmer periods, as between Julian day 64 and 70, almost no cirrus were detected, despite the high number of lidar observations. The downward propagating Kelvin waves can best be recognized at altitudes above 17 km. They show a wavelength of about 12 days with an amplitude of more than 5 K.

[25] The analysis of the three additional field campaigns in July and October 1999 and in March 2000 shows the same wave characteristics in the lower stratosphere. Because of the shorter duration of these campaigns the graphs are less representative and are not presented in this study.

[26] As shown in Figure 2c the occurrence of cirrus was, however, also strongly correlated with the distance to deep convection. The data for the bar chart in Figure 2c were calculated from the CDC OLR data set (see section 2.3). For each Julian day, the bars show the geographical distance between Hulule (Maldives), where the lidar was located, and the nearest location with deep convection. It is obvious from the graph that especially between Julian day 70 and 85 there was strong convective activity close to Hulule. On day 75, corresponding to 16 March 1999, deep convection was observed directly at the lidar site.

[27] Also cirrus statistics based on satellite-borne lidar measurements, as with the ICESat/Geoscience Laser Altimeter System (GLAS), reveal an increase of the occurrence frequency of cirrus with decreasing OLR [Dessler et al., 2006]. However, an investigation on the connection between the occurrence of cirrus and stratospheric waves, as done here, was not performed.

[28] A clear separation of the processes that control cirrus formation is not possible from our INDOEX data. Figure 2 suggests that cirrus occurrence in general increases when strong cold perturbations in the upper troposphere occur, and that, during such perturbation events, convective activity also increases, possibly linked to the cold perturbation. Seasonal means and mean distance of areas of deep convection to the lidar site at Hulule are given in Table 1.

3.2. Cirrus Geometrical Properties

[29] Table 2 and Figures 3 and 4 summarize the observational results concerning the geometrical and thermal properties of cirrus. To avoid a possible, unwanted inclusion of altostratus, i.e., of water clouds, we restricted the analysis to clouds with cloud base heights ≥9 km. As can be seen from Table 2, rather similar geometrical properties were found during the NE and SW monsoon seasons.

[30] Figure 3 shows seasonal and total frequency distributions of cirrus cloud base height, cloud top height, and cloud depth. In 50% out of all cases, the top height was found above 14 km. Base heights show a broad distribution peaking at 12–13 km and 11–12 km height during the NE and SW monsoon season, respectively. Cloud geometrical depth was in about 70% and 50% out of all cases ≤2 km during the NE and SW monsoon season, respectively.
Because of the permanent presence of deep convection around the Maldives during the SW monsoon season (see Table 1, July, October) the detected clouds were most likely often fresh remnants of cumulonimbus anvils. This may explain the higher number of cirrus layers with depths $>2$ km during the SW monsoon season.

Table 1. Seasonal Average and Range of Distance of Deep Convection (OLR < 170 Wm$^{-2}$) to Hulule (Maldives) in Geographical Degrees (1° ≈ 100 km)

<table>
<thead>
<tr>
<th></th>
<th>Mean Distance</th>
<th>Range (Min–Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb/Mar 1999</td>
<td>13°</td>
<td>0–30°</td>
</tr>
<tr>
<td>Mar 2000</td>
<td>13°</td>
<td>8–25°</td>
</tr>
<tr>
<td>July 1999</td>
<td>3°</td>
<td>0–9°</td>
</tr>
<tr>
<td>Oct 1999</td>
<td>2°</td>
<td>0–4°</td>
</tr>
</tbody>
</table>

Table 2. Mean Values and Standard Deviations (in Parentheses) of Geometrical and Thermal Cloud Properties

<table>
<thead>
<tr>
<th></th>
<th>All Cases</th>
<th>NE Monsoon</th>
<th>SW Monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzed cases</td>
<td>179</td>
<td>106</td>
<td>73</td>
</tr>
<tr>
<td>Cloud base height, km</td>
<td>11.9 (1.6)</td>
<td>12.1 (1.6)</td>
<td>11.6 (1.6)</td>
</tr>
<tr>
<td>Cloud top height, km</td>
<td>13.7 (1.4)</td>
<td>13.7 (1.4)</td>
<td>13.7 (1.3)</td>
</tr>
<tr>
<td>Cloud depth, km</td>
<td>1.8 (1.0)</td>
<td>1.6 (0.9)</td>
<td>2.1 (1.2)</td>
</tr>
<tr>
<td>Middycloud height, km</td>
<td>12.8 (1.4)</td>
<td>12.9 (1.5)</td>
<td>12.7 (1.3)</td>
</tr>
<tr>
<td>Cloud base temperature, °C</td>
<td>−50 (15)</td>
<td>−51 (13)</td>
<td>−48 (13)</td>
</tr>
<tr>
<td>Cloud top temperature, °C</td>
<td>−65 (11)</td>
<td>−65 (11)</td>
<td>−64 (10)</td>
</tr>
<tr>
<td>Middycloud temperature, °C</td>
<td>−58 (11)</td>
<td>−58 (11)</td>
<td>−57 (11)</td>
</tr>
<tr>
<td>Tropopause height, km</td>
<td>16.3 (1.0)</td>
<td>16.7 (0.9)</td>
<td>15.5 (0.4)</td>
</tr>
<tr>
<td>Tropopause temperature, °C</td>
<td>−81 (4.0)</td>
<td>−83 (3)</td>
<td>−77 (2)</td>
</tr>
</tbody>
</table>

*Shown are also height and temperature of the lapse rate tropopause. The values are given for all observed cirrus cases as well as for the northeast monsoon and the southwest monsoon.
The following effects must also be kept in mind when discussing possible differences between SW and NE monsoon cirrus. The, on average, very close distance to an area of convective activity during the SW monsoon season suggests that the dissolution process had often not started when clouds were detected at the upper edge of deep convective cells during this season [Liu and Zipser, 2005]. In contrast, NE monsoon clouds usually had their origin in greater distance to the Maldives. Therefore they had already aged before they were detected with the lidar. Entrainment and detrainment of air at the cloud boundaries during the life cycle of the cirrus layer cause a decrease of the cloud thickness until the cloud decays [Platt et al., 1989; Sassen et al., 1989; Sivakumar et al., 2003]. The maintenance of anvil cirrus for several hours to more than a day also requires a slow rise of the clouds by radiative heating. If the cirrus clouds would remain at their initial level, they would dissolve quickly [Ackerman et al., 1988; Jensen et al., 1996].

The location of the tropopause level which on average varied by more than 1 km in height and 6°C in temperature between both monsoon seasons (see Table 2) also played a role in the distribution of the clouds, especially regarding the top heights. Because of the lower tropopause during the SW monsoon season, no cirrus was observed above 16 km at temperatures below −80°C during this season.

Figure 4 shows that the cirrus center heights most frequently were between 11 and 14 km height (in both seasons, see Table 2). Corresponding midcloud temperatures ranged most frequently from 0°C to 7°C. The dependence of cirrus depth on height or temperature was weak with a trend to geometrically thin clouds with decreasing temperature (see Figure 4c).

The general opinion that the occurrence of upper tropospheric cirrus is decoupled from lower tropospheric processes such as deep convection is corroborated by Figures 5 and 6. Upper tropospheric cirrus formed by large-scale uplift or wave activity is usually physically thin and has a laminar structure [Pfister et al., 2001]. A sharp depth distribution peaking at 400–800 m is found for clouds with cloud base above 14 km. Anvil cirrus appears more structured, has variable cloud boundaries, and thus is characterized by a broad distribution of geometrical depths.

Figure 6 shows the distribution of the distance of the cirrus cloud top to the lapse rate tropopause for the different cirrus types (laminar cirrus above 14 km, anvil cirrus). The graph contains the data of 140 cirrus cases of both monsoon seasons. The radiosonde ascent that was closest to the lidar observation was used in Figure 6. Two distinct maxima are found. One maximum of occurrence is located close to the tropopause level. The lower maximum is obviously related to anvil cirrus from cumulonimbus clouds.

The 4-year geometrical cirrus cloud statistics of the tropical Indian station Gadanki (13.5°N, 79.2°E) presented by Sivakumar et al. [2003] and Sunilkumar and Parameswaran [2005] agree well with the Maldives data.
set. A very similar occurrence frequency distribution of cloud depths as shown in Figure 3g was observed over Gadanki. The midcloud height distribution was similar to that presented in Figure 4a. The distribution of the cloud depth per midcloud temperature interval as shown in Figure 4c is in good agreement with the observations performed at Gadanki as well as at Nauru and the Seychelles. Comstock et al. [2002] analyzed lidar data collected at Nauru (0°, 167°E) in the western Pacific region which is known to have the highest altitude of occurrence of thin cirrus clouds [Wang et al., 1996] and Pace et al. [2003] characterized clouds at the Seychelles (4.4°S, 55.3°E) by means of lidar.

[38] The comparison of the Nauru [Comstock et al., 2002] and the Maldives data sets further reveals that the cloud top in the western Pacific region was most frequently around 16 km at Nauru and around 14–15 km at Hulule. The cloud base was typically found about 2 km below cloud top at both tropical sites. A higher mean tropopause height of 16.9 km over the western Pacific warm pool [Sassen et al., 2000] in contrast to the 16.3 km height over the Maldives (see Table 2) implies differences in the meteorological conditions between both regions. High sea surface temperatures in the western Pacific region are also supposed to enhance deep convection [Ramanathan and Collins, 1991; Liu and Zipser, 2005]. Similar characteristics of cloud depth distributions as shown in Figure 5 were also found by Comstock et al. [2002] and Pace et al. [2003].

[39] Cloud top distributions based on a 5-week data set obtained with the spaceborne ICESat/Geoscience Laser Altimeter System (GLAS) confirm these findings [Dessler et al., 2006]. The GLAS measurements show that the highest frequency and highest cloud heights of cirrus occur over the western Pacific warm pool. Lower cloud frequencies and lower heights are reported for the tropical Indian Ocean over the Maldives.

[40] Sivakumar et al. [2003] also investigated the distances from cloud top to the tropopause (see Figure 6) and found one maximum right below the tropopause and another one about 3 to 4 km below the tropopause. However, in contrast to the findings for the Maldives region, besides the 25% of the cirrus clouds at Gadanki that were close to, but below the tropopause, another 25% of all clouds were reported to have appeared in altitudes up to 3 km above the tropopause. This is possibly caused by the fact that Sivakumar et al. [2003] used radiosonde data from a station located 120 km away from Gadanki where radiosondes were launched at fixed times.


[42] Most of the midlatitude cirrus clouds begin to form in the uppermost troposphere close to the tropopause. The top heights were found most frequently from 11–12 km height over northern Germany as well as over Utah. 70% of the observed cirrus top heights coincided with the tropopause height over northern Germany [Reichardt, 1999]. Mean midcloud height was at 11 km ± 2 km over Utah. A broad frequency-of-occurrence distribution for the cloud thickness from a few hundred meters to 7 km was found over Utah with a mean value of 1.8 km [Sassen and Campbell, 2001]. The mean cirrus depth was 2–2.5 km over Oklahoma [Wang and Sassen, 2002]. These values are very similar to the mean cloud depths presented in Table 2. Most ice clouds had a thickness of 0.5–2.5 km (75% out of all cases) over the more northern midlatitude sites in northern Germany.

3.3. Cirrus Optical Properties

[43] The cirrus data set for the retrieval of cirrus optical properties was considerably smaller (96 cases) than the total data set of 179 cirrus observations. In many cases low-level clouds temporarily obstructed the cirrus layers so that the time periods left for the optical properties retrieval were often too short resulting in a too low signal-to-noise ratio. In several cases with strong variations of cloud structures and optical properties with height and time, a reliable retrieval of the optical depth based on the averaged signal profile was not possible [Ansmann et al., 1992].

[44] An overview of the optical properties of the analyzed clouds is given in Tables 3 and 4. The classification of the cloud types in Table 3 follows the scheme of Sassen and Cho [1992]. They defined cirrus clouds with $\tau < 0.03$ as subvisible cirrus, clouds with $0.03 < \tau < 0.3$ as thin cirrus, and clouds with $\tau > 0.3$ as opaque cirrus. According to Table 3, 15% of all analyzed cirrus cases were subvisible cirrus, about 50% thin cirrus, and 36% opaque cirrus. More
subvisible cirrus (18%) was observed during the NE monsoon than during the SW monsoon season (8%). The seasonal mean values of the optical depth, the cirrus layer mean extinction coefficient (ratio of optical depth to geometrical depth), and cirrus lidar ratio indicate almost the same optical properties during both SW and NE monsoon seasons. The Nauru observations (0°S, 166°W, April–November 1999), also SW monsoon season) reveal more subvisible cirrus (20–25%) and more thin cirrus (60–70%).

Table 3 provides an overview of the mean values of cirrus optical properties considering all cases and, separately, anvil (≤14 km) and remaining laminar or nonanvil cirrus clouds. The higher frequency of subvisible cirrus during the NE monsoon season led to the lower mean cirrus optical depth when compared with the SW monsoon season. The average values of the cirrus layer mean extinction coefficient are remarkably similar for the different seasons. Differences in the lidar ratio mean values for the different seasons are also found to be small (Table 4). Only for thin cirrus a considerable difference is found (Table 3). The lidar ratio statistics is discussed in more detail below.

[46] Mean values of cirrus optical depth, cirrus layer mean extinction coefficient, and lidar ratio for 10 K temperature intervals are presented in Figure 7. As expected, the optical depth and mean extinction coefficient decreased with decreasing temperature for typical cirrus temperatures of ≤−40 °C. The impact of increased convective activity during the SW monsoon in comparison to the NE monsoon is indicated by larger values of optical depth and extinction coefficient at higher temperatures.

[47] Sunilkumar and Parameswaran [2005] present a relatively strong, almost exponential increase of the optical depth with increasing temperature for the Gadanki data set. Their optical depth values are lower than those determined from the Maldives data, with, e.g., a mean optical depth of about 0.15 for temperatures between −40 and −50°C compared to 0.35 over the Maldives.

[48] The analysis of the data set from the Seychelles [Pace et al., 2003] revealed a rather constant average optical depth of about 0.7 at temperatures >−60°C. However, at temperatures between −60 and −90°C the optical depth decreased rapidly from about 0.5 to 0.003. Reasons for the observed differences between the three data sets of Gadanki, the Seychelles, and the Maldives are unclear. They might result from different data analysis methods including the approach to correct for multiple scattering effects. Another reason may be differences in the definition of a single cirrus cloud layer. Pace et al. [2003] defined cloud layers separated by more than 400 m as different clouds. In the present study layers were evaluated separately when more than 800 m of clear air appeared between them. Thinner clouds would also lead to lower optical depths. For the analysis of the Gadanki data set, Sunilkumar and Parameswaran [2005] applied a constant lidar ratio of $S = 20$ sr to all cirrus cases. This leads to an underestimation of the optical properties.
depth of clouds that actually had a higher lidar ratio. On average, the cirrus lidar ratio was 30–35 sr at Hulule (see Tables 3 and 4 and Figure 7).

[49] The comparison of the optical properties of our tropical data set with respective midlatitude observations reveals that in midlatitudes subvisible, thin, and opaque cirrus occurred in about 10%, 60–65%, and 25–30% of all cases over central Europe [Reichardt, 1999] and Oklahoma [Wang and Sassen, 2002], and roughly 10%, 30%, and 60% over Utah [Sassen and Comstock, 2001]. Mean cirrus optical depth was 0.58 over Oklahoma and 0.75 over Utah [Sassen and Comstock, 2001], and about 0.25–0.3 above northern Germany [Ansman et al., 1993; Reichardt, 1999] as at Hulule (Table 4).

[50] In order to accurately determine the radiative properties of clouds, improved knowledge on the cirrus extinction coefficient \( \alpha \) as a function of temperature \( T \) is a basic requirement [Heymsfield and McFarquhar, 2002]. Parameterization functions determined from distributions of the extinction coefficient dependent on temperature are useful to improve cirrus modeling. The parameterization function derived from the INDOEX data set is shown in Figure 8 (solid line). The equation is a polynomial function of second-order of the form

\[
\frac{\alpha}{C_2} = 0.5072 + 8.91 \times 10^{-3} T + 4.15 \times 10^{-5} T^2
\]

For comparison additional fit functions are presented for the tropical region of Gadanki (dashed-dotted line [Sunilkumar and Parameswaran, 2005]) and for the midlatitudinal region of Oklahoma, USA (dashed line [Wang and Sassen, 2002]). Retrieved cirrus layer mean extinction coefficients from the ICE data set (northern Germany, open squares [Ansman et al., 1993]) are shown in addition. Good agreement is found for the Maldives and Oklahoma data sets when taking the standard deviations (INDOEX, solid circles) into account. Almost the same decrease of the extinction coefficient with decreasing temperature is found. The respective polynomial function for the Gadanki data deviates strongly from the INDOEX polynomial function, obviously the result of differences in the lidar data analysis and the retrieval assumptions. Good agreement is also found with ICE extinction-versus-temperature behavior.

[51] The distribution of the INDOEX cirrus lidar ratios versus temperature is shown in Figures 7g–7i and 9. Although the mean values of the cirrus lidar ratio for the different seasons, different optical depth classes, and cloud types (anvil, nonanvil) are very similar with values from 27–36 sr (Tables 3 and 4), Figures 9 and Figure 7 indicate some differences between the seasons. 63% of the NE monsoon lidar ratios in Figure 9 are >30 sr and are well distributed over the 27–57 sr range (80% out of all NE monsoon cases), whereas 68% of the SW monsoon lidar ratios are <30 sr and accumulate from 16–31 sr (80% out of all SW monsoon cases). A clear dependence on temperature is not obvious.

[52] According to model calculations [Reichardt et al., 2002] of optical properties of ice crystals with weak shape distortion (slight deviations from the regular hexagonal structure and a rough surface) column-like crystals mostly produce lidar ratios of the order of 5–20 sr, whereas plate-like crystals lead to lidar ratios in the range predominantly from 15–35 sr. The model study further shows that the lidar ratio is rather sensitive to the crystal shape and especially to deviations from the ideal hexagonal structure (pristine particles). With increasing distortion (irregularity) the lidar ratios increase. It can be concluded that the lidar ratios for larger, more complex crystals that are assumed to show a
higher degree of distortion than small crystals, are considerably larger than 30 sr [Reichardt et al., 2002].

[53] According to these simulations one may conclude that the crystals were, on average, smaller and of more regular shape during the SW monsoon season than during the NE monsoon season. One reason for this finding may be that the majority of SW monsoon lidar ratios was determined in anvil cirrus (Figure 9). On the other hand, if we only consider the lidar ratios for the anvil-cirrus temperature range (midcloud temperatures of about $\geq -60 \pm 5^\circ C$ in Figure 9) the NE-to-SW differences remain. Different meteorological conditions and different aerosol conditions (polluted northern hemispheric air versus pristine southern hemispheric air) may have caused this difference (see discussion in section 4).

[54] It is interesting to note that a similar behavior (influence of convection) of the lidar ratio was found by Whiteman et al. [2004] at the Andros Islands (25°N, August–September 1998), Bahamas. When they excluded hurricane-influenced observations, they found a steady increase from about 15–17 ± 10 sr at −30°C over 22 ± 8 sr at −50°C to 28–33 ± 12 sr at temperatures around −70°C. When considering the hurricane-influenced cases (deep convection up to 16.5 km or −80°C) the mean lidar ratios decreased to values of roughly 15–22 sr for the temperature range from −60°C to −80°C. The impact of strong convection seems to lower the lidar ratio. Stronger convection may initiate the formation of a larger number of crystals that then show a smaller mean size and more simple forms with regular structures (hexagonal columns and plates). The lidar ratios were mostly in the range from 10–40 sr (mean values of 20 ± 8 sr) over the Andros Islands. Multiple scattering was estimated to be of minor importance (5% impact) and thus not corrected. Some lowering of the lidar ratios due to specular reflection (strong backscatter coefficients in the case of a vertically pointing lidar) cannot be excluded in this statistics.

[55] Similar lidar ratios as observed during INDOEX were also derived from lidar observations in Taiwan (25°N, August 1999 to July 2000) presented by Chen et al. [2002]. About 90% of their measured, multiple-scattering-corrected values were ≤50 sr. In the height ranges from 12–15 km (−50 to −70°C) they found single-scattering-related lidar ratios of about 35 ± 15 sr. For heights between 15–16 km (−73 ± 3°C), the mean lidar ratio was 20 ± 8 sr.

[56] Seven-year observations of the cirrus lidar ratio over Utah revealed mean values of about 35, 27, 22, 22, and 21 sr for optical depths around 0.12, 0.25, 0.5, 1, 1.2, and 2.5, respectively. Most retrieved values ranged from 15–60 sr [Sassen and Comstock, 2001].

[57] As mentioned by Whiteman et al. [2004], cirrus lidar ratios from about 10–50 sr are in strong contradiction to values published by Platt et al. [2002] (Melville Island, in northern Australia, 11°S, November–December 1995) for tropical cirrus. They found mean lidar ratios of 104 ± 20 sr (−75°C), 90 ± 25 sr (−65°C), 47 ± 20 sr (−55°C), 48 ± 20 sr (−45°C), and 39 ± 18 sr (−35°C), respectively, by applying the so-called LIRAD (lidar radiometer) technique.

[58] In the LIRAD method the backscatter coefficient is measured with the lidar, whereas the visible extinction coefficient is estimated from the column IR absorption coefficient measured radioradiometer. Obviously, the visible extinction coefficient for the cirrus layer is significantly overestimated by using the LIRAD method [Sassen and Comstock, 2001]. This overestimation appears to increase with increasing height (decreasing temperature) of the cirrus layer. A similar discrepancy between Raman lidar and LIRAD observations of midlatitude cirrus lidar ratios was already found earlier [Ansman et al., 1992].

4. Anthropogenic Aerosol Effects on Cirrus Clouds

[59] Chylek et al. [2006] investigated the effect of aerosols on the size distribution of cloud droplets and ice crystals based on observations with the spaceborne MODIS (Moderate-resolution Imaging Spectroradiometer). They found a larger effective radius of ice crystals in cirrus clouds over the Indian Ocean adjacent to the Indian subcontinent during episodes of increased pollution (January of 2001–2005) than during the more clean SW monsoon season (September of 2000–2004). They proposed a combination of natural seasonal variability of meteorological conditions and an “inverse aerosol indirect effect” (i.e., a decrease in ice crystal numbers accompanied by growth into larger sizes) caused by heterogeneous ice nucleation as a possible explanation of the observed ice crystal growth. They argue that this “inversion” may occur when pollution aerosol supply heterogeneous ice nuclei (soot particles, dust particles) that initiate ice nucleation at supersaturations lower than those needed for homogeneous nucleation. This causes ice to form and grow on these heterogeneous ice nuclei first, thereby reducing the ambient water concentrations and supersaturation so that many of homogeneous ice nuclei are not activated, thereby decreasing the total number of ice crystal concentration.

[60] As observed with our lidar, aerosol layers reached into heights of up to 4 km during the NE monsoon season [Franke et al., 2003] (note, in addition, the aerosol pollution layers in Figures 1a and 1b). The particle optical depth was found to be a factor of three higher during the NE monsoon season over the Maldives compared to conditions during the clean SW monsoon season. Above 4 km the atmosphere was always rather clean according to the lidar observations. Under such conditions the following effect may occur: Deep convection that is initiated in such pollution layers below 4-km height may be considerably affected by the enhanced concentration of aerosol particles. These particles may act as additional cloud condensation nuclei (CCN [Twomey, 1974]). For a constant liquid water content, enhanced particle concentrations may thus increase the cloud droplet number concentration, and decrease the mean cloud droplet diameter. Heymsfield and McFarquhar [2001] reported droplet number concentrations in maritime convective clouds north of the ITCZ that were up to five times higher than in convective clouds south of the ITCZ. The decrease of the effective droplet radius was also reported by Chylek et al. [2006].

[61] In the case of smaller droplets an important ice production process in tropical clouds, the Hallett-Mossop process [Hallett and Mossop, 1974; Mossop and Hallett, 1974; Pruppacher and Klett, 1997], might be suppressed [Rosenfeld and Woodley, 2000]. The Hallett-Mossop process describes the important role ice particle splintering
plays during the riming process in clouds. The resulting ice splinters act again as ice nuclei, supporting the Bergeron-Findeisen ice production process. In order to be effective, the Hallett-Mossop process requires relatively high number concentrations of large droplets. Since droplets are comparably small in polluted clouds, ice production at relatively high temperatures might be less effective than it would be in clean maritime clouds. Hence more droplets would be lifted up to altitudes with temperatures below −37.5°C. At such temperatures the droplets finally freeze homogeneously to plate- and column-like ice crystals [Hallett et al., 2002]. According to this theory, cirrus clouds (anvil cirrus) that are influenced by anthropogenic pollution should have more and smaller ice particles than pristine cirrus clouds [Ramanathan et al., 2001]. In comparison to cirrus not affected by pollution, the comparably high concentration of ice crystals should lead to higher values of the cloud mean extinction coefficients and possibly lower lidar ratios (caused by smaller and more regular ice crystals) during the NE monsoon season.

Our INDOEX observations reveal rather similar cirrus layer mean extinction coefficients for the different NE and SW monsoon seasons. As shown in Table 4, the mean values of the extinction coefficient were 0.16 ± 11 (NE) and 0.14 ± 0.11 (SW) for anvil cirrus. On the other hand, the column lidar ratios of anvil cirrus show considerable differences between the seasons. Higher values were found during the NE monsoon season supporting the findings of Chylek et al. [2006]. Here, we assume that higher lidar ratios indicate a higher degree of irregularity of the ice crystal shapes, that in turn is linked to the presence of more complex and thus larger ice crystals. When considering only the anvil cirrus clouds in Figure 9, about 74% of the NE monsoon cirrus lidar ratios are larger than 27 sr, whereas the SW monsoon anvil cirrus lidar ratios still accumulate between 16–31 sr (80% out of all anvil cirrus cases).

As Whiteman et al. [2004] mentioned, deep-convection-related cirrus show lower lidar ratios than laminar, nonanvil cirrus. It cannot be excluded that many ice clouds with top heights below 14 km during the NE monsoon season were still nonanvil cirrus. As was discussed above, during the NE monsoon season, aged cirrus was frequently observed that may have descended from above 14 km, while during the SW monsoon season, freshly formed anvil cirrus dominated.

It also cannot be excluded that the lidar ratio increases (indicating an increasing irregularity effect of the crystals) with increasing lifetime of the ice cloud, although it appears unlikely that the degree of crystal shape irregularity increases with time in a slowly dissolving and evaporating cirrus [Reichardt et al., 2002].

The difference in the extinction-to-backscatter characteristics in ice clouds below 14 km height is consistent with the findings of Chylek et al. [2006] stating that effective cirrus particle size increases with increasing aerosol optical depth (increasing impact of aerosol pollution). However, because significant differences in the meteorological conditions, especially below 14 km height, was also observed during the NE and SW monsoon seasons, the differences in the lidar ratios can also be simply explained by natural effects without the need of an anthropogenic effect. Thus an unambiguous conclusion regarding the influence of Asian haze on tropical cirrus clouds cannot be drawn from our data.

5. Summary

We analyzed the INDOEX lidar-radiosonde measurements with respect to the geometrical and multiple-scattering-corrected optical properties of 179 different ice clouds with base above 9-km height as a function of height and temperature. Satellite observations of convective activity (OLR) together with the temperature profiles of the 250 INDOEX radiosondes were used to study the impact of deep convection and stratospheric waves on cirrus formation over the lidar site in the tropical Indian Ocean. We found that the occurrence of cirrus clouds correlates to both, the distance to deep convection and the phase of stratospheric waves. Statistics of geometrical and optical cirrus properties were presented for the entire data set as well as separately for the dry, aerosol-polluted NE monsoon and the rainy SW monsoon season. Average values of the cirrus properties varied significantly between the two seasons. They were most likely caused by contrasting meteorological conditions. Cirrus clouds covered the sky over the lidar site in only 35% of the measurement time during NE monsoon, but 64% during SW monsoon. With 2.1 ± 1.2 km cloud geometrical depth during the SW monsoon was shifted to larger values compared to the NE monsoon (1.6 ± 0.9 km). Mean midcloud heights were rather similar with values of 12.9 ± 1.5 km during NE and 12.7 ± 1.3 km during SW monsoon. 25% of all observed clouds reached the tropopause level but less than 4% were observed above it.

According to their optical depth the cirrus clouds were separated into subvisible (optical depth ≤0.03), thin (optical depth from 0.03 to 0.3), and opaque cirrus (optical depth ≥0.3). Thin cirrus was the dominating cirrus type during both seasons (48% during NE and 52% during SW monsoon). The lower impact of deep convection during the NE monsoon is expressed in higher frequencies of subvisible cirrus (18% compared to 8% during SW monsoon) but less opaque cirrus (34% compared to 40% during SW monsoon). The average optical depth of all observed cirrus clouds also showed significant seasonal differences, differing between 0.25 ± 0.26 during NE and 0.34 ± 0.29 during SW monsoon. The average extinction-to-backscatter ratio was lower during SW monsoon (29 ± 11 sr) than during NE monsoon (33 ± 9 sr). The average of the cirrus layer mean extinction coefficient equaled for both seasons (0.12 ± 0.1 km⁻¹).

Comparisons of the results of the INDOEX measurements with other tropical, subtropical, and midlatitude cirrus studies were presented. Similar optical properties were mainly found for the different regions. For better comparison parameterizations of the temperature dependence of the cirrus extinction coefficient were presented for 4 different cirrus studies. Observed differences in the geometrical properties can mostly be explained by differing meteorological conditions. Over the INDOEX region cirrus was detected less frequent and at lower heights in comparison to studies based on data sets from the western Pacific region and the southwestern Indian Ocean. A cirrus study based on measurements of the spaceborne ICESat/Geoscience Laser Altimeter System (GLAS) found a similar distribution of
cirrus clouds over the Indian Ocean as reflected in the field studies conducted in this region.

[60] Cirrus optical properties observed during the polluted NE monsoon season and the clean, maritime SW monsoon season were compared to identify a possible impact of man-made aerosols on ice formation and the optical properties of ice clouds. Cirrus layer mean extinction coefficients were rather similar during both seasons. Lidar ratios, on the other hand, were found to differ between NE and SW monsoon season suggesting more irregularly shaped and thus larger ice crystals during the NE monsoons season than during the SW monsoon season. Large ice crystals during the NE monsoon season were also derived from satellite data [Chylek et al., 2006]. A clear conclusion concerning a possible impact of anthropogenic haze on cirrus properties is not possible because of significantly different meteorological conditions during the different seasons that can also be responsible for the found differences.

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