GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 23, 2090, doi:10.1029/2002GL015076, 2002

Determination of tropical cirrus properties by simultaneous LIDAR and radiosonde measurements

Franz Immler and Otto Schrems

Alfred Wegener Institute for Polar and Marine Research, Germany

Received 8 March 2002; revised 8 July 2002; accepted 11 July 2002; published 4 December 2002.

[1] High-altitude tropical cirrus (TC) have been observed by lidar during a cruise of the German research vessel 'Polarstern' above the Atlantic between 8°S and 12°. The backscatter lidar data give a detailed picture of the vertical structure of the clouds with a high time resolution. Using the data of radiosondes, which were launched twice a day aboard 'Polarstern,' the temperature of the clouds as well as the structure of the tropical tropopause is characterized. The clouds are found in an altitude between 14 km and 17 km, with a mean optical depth of τ = 0.02 and a mean temperature of 198 K. Tropical Cirrus appear in two distinct layers which are separated by a change in wind direction. This structure was observed south as well as north of the ITCZ. Cloud tops are often found at the thermal tropopause, in some case these clouds are of the ultra-thin type. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0394 Atmospheric Composition and Structure: Instruments and techniques; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Immler, F., and O. Schrems, Determination of tropical cirrus properties by simultaneous LIDAR and radiosonde measurements, *Geophys. Res. Lett.*, *29*(23), 2090, doi:10.1029/2002GL015076, 2002.

1. Introduction

[2] Recently, thin cirrus along the tropopause have been reported to be common in the tropical regions [*Winker and Trepte*, 1998; *Omar*, 2001; *Pfister et al.*, 2001]. These clouds often extend to more than 1000 km horizontally and persist for up to several days. Due to their ubiquitous nature the tropical cirrus have an important influence on the radiative balance in the tropics and therefore on global climate [*McFarquah et al.*, 2000]. However, the physical processes that allow the formation and maintenance of the tropical cirrus are not yet readily understood. Models that explain the high altitude clouds as remnants of cirrus outflow anvils from deep convection can not reproduce their enormous size in time and space. It is still unknown how the clouds are able to maintain themselves against the processes of sedimentation and evaporation [*Boehm et al.*, 1999]. It is therefore hypothesized that large scale upward motion has to be present to support the cloud by supplying adiabatic cooling and moisture. In this case tropical cirrus occurrence is strongly related to the ascent of tropospheric air into the stratosphere. Thus, tropical cirrus clouds play a key role in determining the abundance of water in the stratosphere. *Rosenfield et al.* [1998] suggest that tropical high-altitude cirrus (TC) reduce the water vapor mixing ratio by radiatively heating the tropopause. *Jensen et al.* [2001] pointed out that sedimentation of ice particles in ascending air at the tropopause can reduce the water vapor mixing ratio of stratospheric air in its source region. Their model creates very thin clouds ($\tau = 10^{-4}$) at the tropopause where adiabatic cooling is balanced with radiative warming, and sedimentation with ascent. Depending on aerosol number density and composition, the tropospheric air is freeze-dried while entering the stratosphere.

[3] Our understanding of these important processes suffers of a lack of available observations as a result of their high altitudes and remote regions. Here, we present measurements performed aboard the German research vessel 'Polarstern' during a cruise from Punta Arenas/Chile to Bremerhaven/Germany in May and June 2000. High altitude cirrus were observed with lidar between 8°S and 12 °N from May 30th to June 3rd. Two radiosonde launches per day around 10:00 and 15:00 UTC provide temperature, wind, humidity and - once per day - also ozone profiles. These data give an interesting insight into the conditions of the tropopause region under which tropical cirrus clouds exist.

2. Instrumentation and Data Analysis

[4] The Mobile Aerosol Raman Lidar (MARL) is a backscatter lidar based on a linear polarized Nd:YAG Laser with 30 Hz repetition rate and 200 mJ pulse energy at 532 nm and 355 nm. The backscattered signal is detected by means of a 1.1 m cassegrain telescope and a multi-channel polychromator. The elastic backscatter at both wavelengths is separated in parallel and perpendicular polarization and detected by photomultipliers. The vertical and the time resolutions for all channels are 7.5 m and 140 s (averaged over 4096 single laser shots), respectively. Owing to narrowband filters and a field-of-view of only 0.45 mrad, the system is capable for day- and nighttime operation.

[5] The lidar equipment is mounted in a standard 20 ft container and therefore easily transportable. During the cruise ANT XVII/4 of 'Polarstern', the system was placed at the vessel's upper deck and operated continuously, whenever weather conditions were appropriate. Low cloud coverage, rain or heavy sea stopped the measurements.

[6] The lidar signals are inverted using a modified *Klett* [1985] algorithm. More details about the inversion methods are found in *Beyerle et al.* [2001]. The density of the molecular atmosphere is determined using radiosonde data. Clouds are detected in the upper troposphere by enhanced backscattering from particles. Here a cloud is defined as every atmospheric feature that creates a peak 10 times

0094-8276/02/2002GL015076$05.00

higher than the noise level in the backscatter ratio profile. Clouds with a backscatter ratio of $R = 2$ and a vertical extent of a few ten meters - corresponding to an optical depth (τ) of below 10^{-3} -are resolvable with the lidar. For thin clouds ($\tau < 0.1$) τ can be estimated from the backscatter profile using an extinction to backscatter ratio $g = 25$. Clouds with $\tau < 10^{-3}$ leave only a weak signal in the parallel backscatter. However, due to the low depolarization of the molecular atmosphere they are well detectable in the cross polarized channel as long as they are composed of solid particles and thus do depolarize. Again using $g = 25$ and a depolarization of 30%, the lower detection limit can be estimated to 10^{-4}. This estimates are accompanied by appreciable errors as discussed e.g. by *Goldfarb et al.* [2001]. However, the accuracy is sufficient to determine at least the order of magnitude of the optical depth of cirrus. Recent reports on the detection of "ultra-thin" cirrus by lidar [*Peter*, 2000] can therefore be confirmed with our system. Lidar proofs to be a uniquely sensitive tool to detect and investigate subvisual cirrus clouds from the ground.

[7] The high vertical resolution of the system enables us to resolve the vertical structure of the clouds and to detect multi-layers. Clouds which are separated by more than 150 m are treated individually in the further data analysis.

[8] The measured quantities are the clouds base and top height, the backscatter ratio and the mean particle depolarization. Using data from the radiosondes one can also infer the clouds base and top temperature. The relative humidity measured by the sondes are unfortunately not reliable due to the very low temperature and low pressure in the tropopause region of the tropics. However, in five cases lidar measurements and radiosonde sounding were performed simultaneously (Figure 2). This gives us the unique opportunity to precisely determine the temperature and the dynamic conditions of the tropopause region.

3. Observations

[9] 120 hours worth of data were gathered during the whole cruise. 43 hours refer to midlatitudes. Another 28 hours of measurements were made in the subtropics (30° to 23°) where no cirrus could be detected at all. In the inner tropics (23°S to 23° N) 47 hours of measurements were performed, during 34 of which cirrus was detected. Most of this cirrus (30 hours) can be described as high altitude tropical cirrus (TC). Between 8°S and 12°N every single measurement shows the presence of TC giving the impression that one single cloud was observed within the 4 days lasting cruise across 2200 km straight north.

[10] Estimates of the optical depth of the TC varied between 10^{-4} and 0.1 with a mean of 0.02, which is just below the visibility threshold of 0.03 [*Sassen et al.*, 1989]. While 80% of the tropical cirrus are below that value, 20% are above. These data agree well with SAGE II results on a global scale [*Wang et al.*, 1998], suggesting that the cirrus clouds probed during the cruise were representative for TC. The mean thickness however was determined to 1.1 km ± 0.6 km, much smaller than the 3.7 km given by Wang et al.. This may be explained by the better vertical resolution of our instrument - increasing the ability to separate multi-layers - and by the tendency of the SAGE II data inversion technique to overestimate the cloud's thickness [*Wang et al.*, 1998].

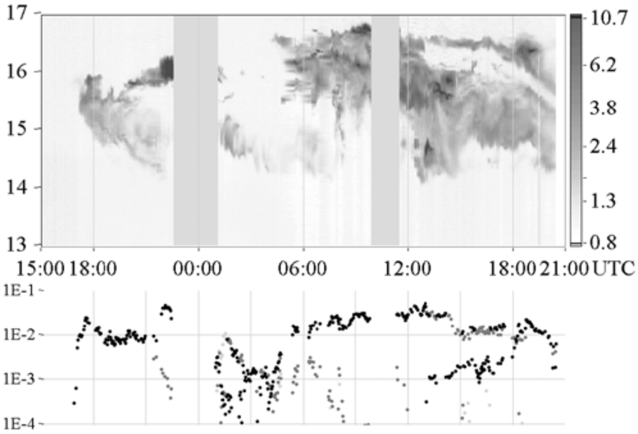

Figure 1. 30 hours of lidar measurement from May 30th, 15:00 UTC to May 31st, 2:00 UTC (= local time + 1.5h): Backscatter ratio at 532 nm as a function of time and altitude. The lower plot depicts the optical depth of the upper (*light grey*) and lower cloud layer. The measurements were performed aboard 'Polarstern' just south of the Equator (9°S to 2°S) at 22°W.

[11] The mean cloud base and top heights were 14.6 km and 15.9 km, respectively. The mean base and top temperature were 200 K and 194K, respectively, 80% of the cloud bases were colder than 205K. This data might be biased by the fact that the radiosondes were launched during daytime only. Around 50% of the TC tops lay within 500 m of the tropopause height, the rest are in mean 1 km below. We may therefore distinguish two TC types: one occurs in the tropical tropopause layer (TTL), while the second type belongs to the upper tropospheric layer (UTL). In most cases these layers are clearly separated. Figure 1 shows lidar backscatter ratio profiles from the 30th and 31st of May 2000. At the right side of the plot, between 13:00 and 21:00 UTC, two layers are separated by a narrow gap, which descends slowly for about 500 m during the 8 hours of observation.

[12] At 13:46 UTC a radiosonde was launched from 'Polarstern', which reached the altitude of the cirrus about one hour later. The lidar backscatter measurement and the temperature profile are shown in Figure 2b. The upper cloud layer appears just below the tropopause at 16.6 km, which is marked by the temperature minimum and a subsequent increase of the ozone concentration. The second, 2 km thick cloud appears in a layer (UTL) which is clearly separated from the TTL by a change in wind direction of approximately 180°. In the upper layer an easterly wind is observed, while in the layer below the wind comes from western directions. Amazingly, this feature is found in most of the radiosonde data, where TC were detected by the lidar (Figure 2). In all cases, clouds exist in the UTL while in some cases the TTL is free of clouds (2d) or only very thin particle layers exist (2e). These last two measurements were made north of the inter tropical convergence zone (ITCZ), while the upper two panels of Figure 2 belong to the region south of the ITCZ. Figure 2c shows a special case where the described TTL is missing. These profiles may be assigned to the ITCZ.

[13] The relation between the clouds occurrences and the tropical circulation was investigated using backward trajec-

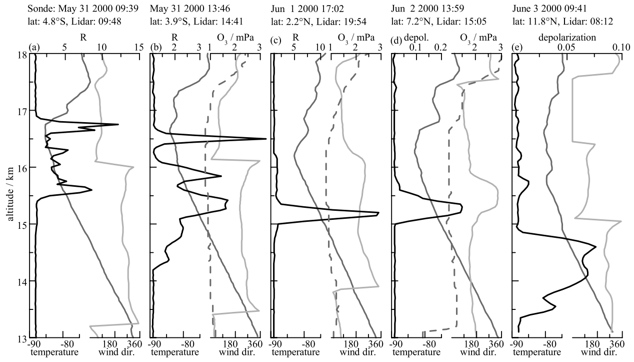

Figure 2. Profiles of temperature (*grey*), wind direction (*light grey*) and ozone (*dashed*, where available). The backscatter ratio or depolarization measured simultaneously (±1 hour) at 532 nm is shown in black. In all cases TC appear in a layer some km below the tropopause with a westerly wind (UTL). This layer is topped by a layer with easterly winds (TTL), which carries thin cirrus in the cases (a), (b) and (e).

tories. These were provided by the British Atmospheric Data Centre (BADC) on the basis of ECMWF horizontal and vertical winds. Figure 3 shows the results for the clouds observed in Figure 2b. The air in the UTL (dashed line) has obviously experienced convection about 3 days before the observation at about 4°N. Subsequently it was advected south-eastward, and after passing the equator it did not experience significant changes in pressure level and potential temperature for 19 hours. The TTL (dotted line in Figure 3), carrying a TC as well, has not been convected from lower altitudes within the last 8 days. However, it also originates from the ITCZ-region and the very low ozone content suggests that the air is purely tropospheric. The different wind directions of the two layers shown in Figure 2b is not reflected in the trajectories, a fact which is throwing some doubts on their reliability in that respect.

[14] Trajectory runs for the other measurements shown in Figure 2 yield similar results, with one exception in case c. Here the air has experienced similar vertical ascent motion in all tropospheric layers just before the observation. Obviously in this case deep convection has reached up all the way to the tropopause. In all the other cases, the trajectories support the concept of two distinct layers at the tropopause. The lower (UTL) may be interpreted as outflow of deep convection from the ITCZ. As Figure 2c suggests, the TTL does not exist in or close to the ITCZ, but forms as the air is advected away by the Hadley circulation. This formation process is of great interest, since it might be the clue to tropospheric-stratospheric exchange processes in the tropics.

[15] During a 'Polarstern' cruise through the tropics in 1996, measurements were carried out with the same instrument [*Beyerle et al.*, 1998]. The situation at that time was different. The layers near the tropopause described above did not exist in the same manner. Instead, this region was warmer, showed a more stable temperature lapse-rate and was free of clouds. The frequency of cirrus occurrence however was still high, but with cloud tops around 14 km altitude, well below the tropopause, at a first inversion layer. This suggests that low temperatures and the dynamical structure of the TTL found in 2000 is related to cirrus formation in the tropopause region.

[16] From the wind profile in Figure 2 one might assume that the TTL and the UTL are strictly detached. However, the lidar data suggest that the clouds probed in both layers have very similar characteristics. This may be seen from Figure 5, where the depolarization is plotted against the backscatter color ratio. Both values are characteristic of the particles' size and shape. This relation is of a complex nature and does not allow for a simple monotone relationship between e.g. depolarization and aspect ratio [*Mishchenko and Hovenier*, 1995]. However, a change in these optical properties indicates differences in the particles habit. Figure 5 shows that both cloud layers are of a similar type. For comparison, data for a midlatitude cirrus measured in Prestwick/Scotland (55°N) in fall 2000 with the same instrument are plotted as well. Obviously the TC exhibit lower depolarization and color ratios suggesting that the crystals are smaller than those of midlatitude cirrus.

[17] In general all observed clouds stay below the tropopause, defined here as the coldest point in the temperature profile. There is one interesting episode, in Figure 1 from 8:40 to 10:00 UTC, where a rather strong layer develops

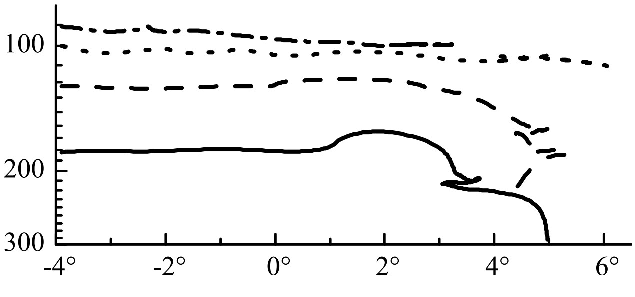

Figure 3. 8-days-backward trajectories from ECMWF analysis, supplied by BADC, calculated for the air probed in Figure 2b. The lower clouds air parcel (*dashed*) went through convection about 4 days prior to the measurement. In the last 19 hours it was on a stable level advected southwestward. The dotted line represents the air parcel carrying the upper cloud from Figure 2b.

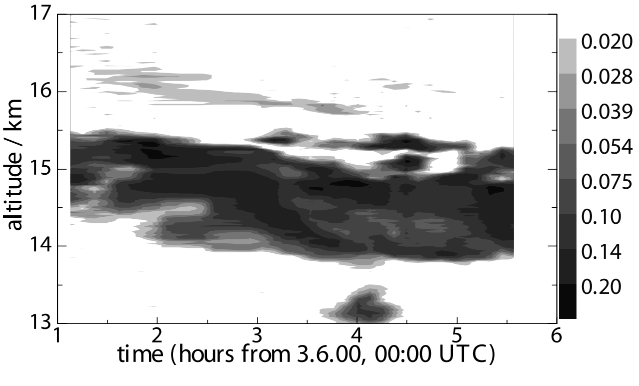

Figure 4. Volume depolarization at 532 nm measured by the lidar on June 3 2000 as a function of time and altitude. Above the TC in the UTL a second weak but significant signal from a ultra-thin cirrus is detected. Its optical depth is estimated to $\tau = 10^{-4}$.

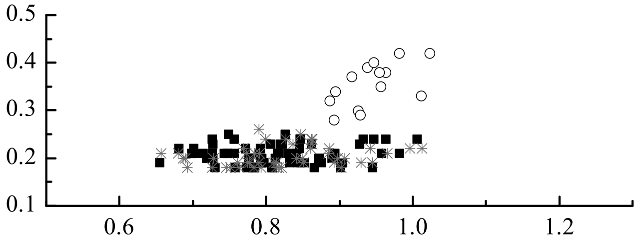

Figure 5. Depolarization versus color ratio for the UTL cloud (*stars*) and the TTL cloud (*squares*) measured on the 31st of May 2000. Both clouds exhibit the same characteristics, suggesting that they have similar microphysical properties. For comparison, values for midlatitude cirrus clouds measured with the same instrument are marked in circles.

right at the tropopause, penetrating it for about 50 m according to the radiosonde launched at 9:36 UTC. During this event the temperature reaches the coldest point (188 K) measured during the whole campaign.

[18] North of the ITCZ, the situation differs from the one in the south in that respect, that no or only very thin clouds were detected in the tropopause layer. Figure 4 depicts the situation in the night of June 3rd, where a persistent cloud layer in the UTL was observed. In the TTL we find evidence for the existence of very thin layers just below the tropopause (Figure 2e). Their optical depth is estimated to $\tau = 10^{-4}$.

4. Conclusion

[19] Thin and subvisible cirrus clouds were found to be very abundant in the tropical tropopause region. The observations reported here give insight in the conditions at the tropopause where tropical cirrus (TC) are forming. Extended and very stable layers have been observed in altitudes between 14 km and 17 km, which are maintaining their vertical structure down to the details on a timescale of hours. Since there is no evidence for a diurnal cycle in the clouds appearance, strong influences of the solar radiation on the cloud formation process are unlikely.

[20] According to radiosonde data, it was found that in most cases two layers in the tropopause may be distinguished: The tropical tropopause layer (TTL) is characterized by easterly winds and reaches from the thermal tropopause to a point, around 1 km lower, where the wind direction changes toward west. This is the upper limit of the second region, the upper tropospheric layer (UTL). Here, cirrus were observed very frequently. According to backward trajectories the airmass of the UTL may be classified as outflow from deep convection in the ITCZ. However, it is unlikely that the observed clouds are remnants from cumulonimbo-anvils because of the long time it has been advected before observation. Since model considerations show that anvils are not able to persist more than about 5 hours [*Boehm et al.*, 1999], yet unknown dynamical or chemical processes have to be involved that help maintain the clouds.

[21] According to *Jensen et al.* [2001] cloud formation by large-scale ascent creates very thin clouds with optical depth below 10^{-3}. Even though we have evidence, that this type of cloud does exist, in general the TC are much thicker. During our campaign we observed a mean thickness of 1.1 km, while the mean optical depth was estimated to be around 0.02. This is in accordance with satellite measurements [*Wang et al.*, 1998].

[22] We observed one event with hints for tropo-stratospheric exchange processes. The temperature at the tropopause was 188 K, close to the ice frost point in the stratosphere [*Marti and Mauersberger*, 1993]. It is obvious, that the formation of cirrus clouds at the tropical tropopause and the dynamical processes observed here have a close link to the dryness of the stratosphere.

[23] **Acknowledgments.** Many thanks to I. Beninga and W. Ruhe (Impres GmbH.) as well as T. Ronge for their support. Thanks to the BADC for the calculation of trajectories and access to data of the European Center for Medium-range Weather Forecast (ECMWF).

References

Beyerle, G., H.-J. Schäfer, R. Neuber, O. Schrems, and I. S. McDermid, Dual wavelength lidar observations of tropical high-altitude cirrus clouds during the ALBATROSS 1996 campaign, *Geophys. Res. Lett.*, *25*, 919–922, 1998.

Beyerle, G., M. R. Gross, D. A. Haner, N. T. Kjome, I. S. McDermid, T. J. McGee, J. M. Rosen, H.-J. Schäfer, and O. Schrems, A Lidar and Backscatter Sonde Measurement Campaign at Table Mountain during Febuary–March 1997: Observations and cirrus clouds, *J. Atmos. Sci*, *58*, 1275–1287, 2001.

Boehm, M. T., J. Verlinde, and T. P. Ackerman, On the maintenance of high tropical cirrus, *J. Geophys. Res.*, *104*(D20), 24,423–24,433, 1999.

Goldfarb, L., P. Keckhut, M. L. Chanin, and A. Hauchecorne, Cirrus Climatological Results from Lidar Measurements at OHP (44°N, 6°E), *Geophys. Res. Lett*, *28*, 1687–1690, 2001.

Jensen, E. J., L. Pfister, A. S. Ackerman, and A. Tabazadeh, A conceptual model of the dehydration of air due to freeze-drying by optically thin, laminar cirrus rising slowly across the tropical tropopause, *J. Geophys. Res.*, *106*(D15), 17,237–17,252, 2001.

Klett, J. D., Lidar inversion with variable backscatter/extinction ratios, *Appl. Opt.*, *24*, 1638–1643, 1985.

Marti, J., and K. Mauersberger, A survey and new measurements of ice vapor pressure at temperatures between 170 and 250 K, *Geophys Res. Lett.*, *20*, 363–366, 1993.

McFarquhar, G. M., A. J. Heymsfield, J. Spinhirne, and B. Hart, Thin and Subvisual Tropopause Tropical Cirrus: Observations and Radiative Impact, *J. Atmos. Sci.*, *57*, 1841–1853, 2000.

Mishchenko, M. L., and J. W. Hovenier, Depolarization of light backscattered by randomly oriented nonspherical particles, *Opt. Lett.*, *20*, 1356–1358, 1995.

Omar, A. H., Observatioins by the Lidar In-Space Technology Experiment (LITE) of high-altitude cirrus clouds over the equator in regions exhibiting extremely cold temperatur, *J. Geophys. Res.*, *106*(D1), 1227–1236, 2001.

Peter, T., Ultrathin Subvisible Cirrus Clouds at the Tropical Tropopaus, *AIP conf. proc.*, *534*, 619–622, 2000.

Pfister, L., H. B. Selkirk, E. J. Jensen, M. R. Schoeberl, O. B. Toon, E. V. Browell, W. B. Grant, B. Gary, M. J. Mahoney, T. V. Bui, and E. Hintsa, Aircraft observations of thin cirrus clouds near the tropical tropopause, *J. Geophys. Res.*, *106*(D9), 9765–9786, 2001.

Rosenfield, J. E., D. B. Considine, M. R. Schoeberl, and E. V. Browell, The impact of subvisual cirrus clouds near the tropical tropopause on stratospheric water vapor, *Geophys. Res. Lett.*, *25*, 1883–1886, 1998.

Sassen, K., M. K. Griffin, and G. Dodd, Optical Scattering and microphysical Properties of Subvisual Cirrus Clouds and Climatic Implications, *J. Appl. Meteor.*, *28*, 91–98, 1989.

Wang, P. H., P. Minnis, M. P. McCormick, G. S. Kent, G. K. Yue, D. F. Young, and K. M. Skeens, A study of the vertical structure of tropical (20°S–20°N) optically thin clouds from SAGE II observations, *Atmos. Res.*, *47–48*, 599–614, 1998.

Winker, D. M., and C. R. Trepte, Laminar cirrus observed near the tropical tropopause by LITE, *Geophys. Res. Lett.*, *25*, 3351–3354, 1998.

F. Immler and O. Schrems, Alfred Wegener Institute for Polar and Marine Research, Germany.