MEASUREMENTS OF AEROSOL AND CIRRUS CLOUDS IN THE UTLS BY A SHIPBORNE LIDAR

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ABSTRACT

Measurements of cirrus clouds and aerosol in the lower stratosphere and upper troposphere have been performed with a mobile lidar system aboard the German research vessel Polarstern. The aerosol load in the lower stratosphere is higher in the tropics compared to the midlatitudes. Our data reveal a high frequency of occurrence of subvisual cirrus clouds in the tropical tropopause region. Based on the data of radiosondes the temperature of the clouds as well as the structure of the tropical tropopause is characterized. The mean optical depth was 0.02 and a mean temperature of 198 K was determined. Cloud tops are often found at the thermal tropopause. In some cases these clouds are extemely thin with an optical depth below 10^{-3}.

1. INTRODUCTION

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 and from Bremerhaven to Cape Town in October and November 2003. High altitude cirrus were frequently observed with lidar in the equatorial region between roughly 10°N and 10°S. Radiosonde launches 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 (TC) exist. These clouds often extend to more than 1000 km horizontally and persist up to a few 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 [1]. 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 [2]. 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. Depending on aerosol number density and composition, the tropospheric air is freeze-dried to a certain degree while entering the stratosphere [3]. However, our understanding of this important processes suffers from a lack of available observations as a result of their high altitudes and remote regions.

Another interesting issue is stratospheric aerosol. Currently, the aerosol load in the stratosphere in general is very low due to the lack of major volcanic eruptions in recent years. This allows a study of non-volcanic sources of aerosol and might also give some insight into the dynamics of the tropical stratosphere, since the aerosol could be used as a passive tracer.

2. INSTRUMENTATION

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.

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. The measurements were only interrupted when low cloud coverage, rain or heavy sea occured.

3. DATA ANALYSIS

The lidar signals are inverted using a modified Klett algorithm [4]. More details about the inversion methods are found in [5]. The density of the molecular atmosphere is determined using radiosonde data. Clouds are detected in the upper troposphere by enhanced backscattering from particles.

A special cloud detection procedure has been developed. It is based on the derivative of the logarithm of raw lidar signals corrected for the Rayleigh contribution. A peak in this signal mark the lower edge of a cloud.

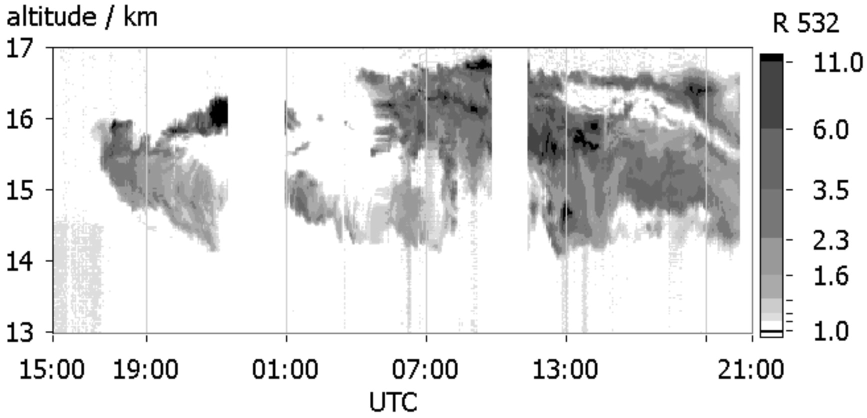

Fig 1: 30 hours of lidar measurement from May 30th, 15:00 UTC to May 31st, 2:00 UTC (= local time + 1.5h): Backscatter ratio at 532 nm as a function of time and altitude. The lower plot depicts the optical depth of the upper (light grey) and lower cloud layer. The measurements were performed aboard 'Polarstern'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

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 depolarize. Again using g = 25 and a depolarization of 30%, the lower detection limit can be estimated to be below 10^{-4}. These estimates are accompanied by appreciable errors as discussed e.g. by [6]. 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 [7] 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.

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.

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. This gives us the unique opportunity to precisely determine the temperature and the dynamic conditions of the tropopause region.

4. OBSERVATIONS

During the first cruise in 2000, high altitude tropical cirrus were present in all measurements between 8°S and 12°N, giving the impression that one single cloud was observed within the 4 days lasting cruise across 2200 km straight north. The SH part of this measurement is shown in Fig.1.

Estimates of the optical depth of this cloud varied between 10^{-4} and 0.1 with a mean of 0.02, which is just below the visibility threshold of 0.03 [8]. 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 [9], suggesting that the cirrus clouds probed during the cruise were representative. The mean thickness however was determined to be 1.1 km ± 0.6 km and thus much smaller than the 3.7 km retreived from the satellite observations [9]. This may be explained by the better vertical resolution of our instrument - improving the ability to separate multi-layers - and by the tendency of the SAGE II data inversion technique to overestimate the cloud's thickness [9].

Comparisons of the lidar with radiosonde data show, that the high cirrus clouds appear in two distinct regions: The lower of which is the upper troposphere with its upper end marked by the tropopause as defined by the lapse rate of the temperature. These clouds were frequently observed during the first cruise in 2000 but rarely during the second in 2003. Above this layer is the tropical tropopause region with its upper edge marked by the cold point tropopause. Here, clouds were also found occasionally and some of them were of the ultra-thin type. This type of cloud was observed several times in the 2003 cruise (Fig. 2) and once during the 2000 cruise. This ultrathin clouds form directly below the coldest point were temperatures as

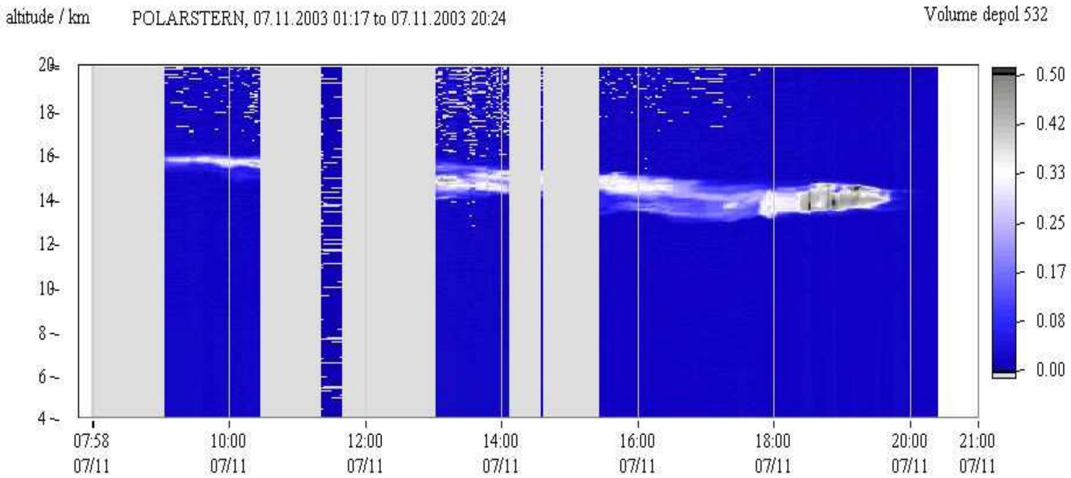

Fig. 2 Volume depolarization at 532 nm measured by the lidar on Nov 7 2003 as a function of time and altitude. A weak but significant signal from is detected from an ultra-thin cirrus. Its optical depth is estimated to $\tau = 10^{-4}$. At 18:00 UTC the properties of the cloud change abruptly and it becomes a thick visible cirrus and then disappears.

low as 188 K are reached. Their optical depth is estimated to $\tau = 10^{-4}$.

Fig. 4 shows profiles of the backscatter ratio at different latitudes. Clearly there is an increasing amount of aerosol in the lower stratosphere with decreasing latitude. The aerosol is evenly distributed in the lower atmosphere up to an altitude of approximately 32 km where the aerosol content sharply decreases to values below the detection limit.

5. DISCUSSION

With a maximum backscatter ratio of about 1.2 the optical depth of the stratospheric aerosol in the tropical region can be estimated to be in the order of 6×10^{-3} assuming an extinction to backscatter ratio of 30. This corresponds to an mean extinction of 3×10^{-4} km^{-1}. This is in good agreement with the values reported by [10] based on SAGE II data.

Interestingly, the tropopause is not clearly marked in the aerosol profiles measured in the tropics in Fig. 4. This could be explained by assuming the source of the stratospheric aerosol in the troposphere. In the tropics, where the air enters the stratosphere by large scale ascent driven by radiative heating, aerosol could have been transported across the cold point tropopause.

A similar but less pronounced picture concerning the strength of the tropical stratospheric aerosol was found during the 2003 cruise in fall. A detailed analysis of the stratsopheric aerosol based on the most recent as well as archived data is currently under weigh.

Thin and subvisible cirrus clouds were found to be very abundant in the tropical tropopause region. Very thin clouds with an optical depth of less than 10^{-3} form occasionally at the cold point tropopause. These clouds are of major importance, since they may play a crucial role for the processes that control the water vapor content of the stratosphere [3].

The observations reported here give insight in the conditions at the tropopause where tropical cirrus (TC) are forming [11]. 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.

The depolarisation of the tropical clouds measured with the lidar suggests, that the tropical cirrus are composed of well defined particle types. This can be concluded from the well defined depolarisation behavior of tropical cirrus compared to that of midlatitude cirrus

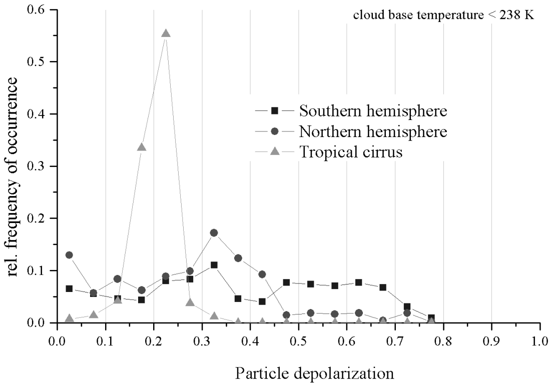

Fig 3: Frequency of occurrence distribution depolarization of cirrus clouds measured in the northern and southern hemisphere [12] with the same instrument compared to that of the tropical cirrus clouds measured during the cruise in 2000.

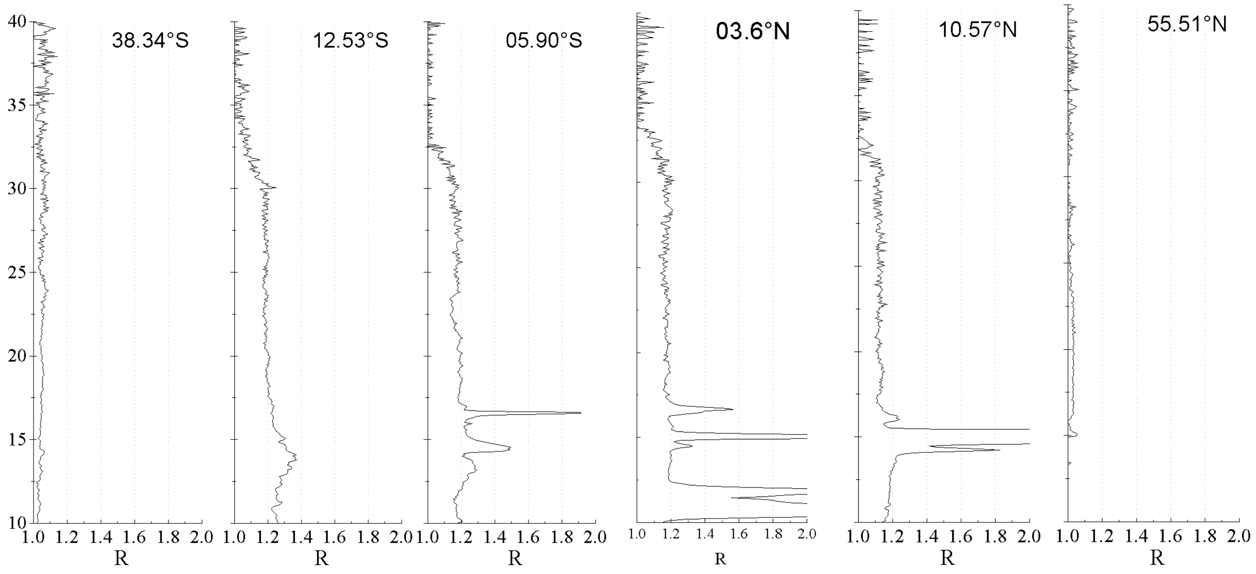

Fig. 4 Backscatter ratio profiles from different latitudes from South to North. While the aerosol load in the midlatitudes is below the detection limit, there is a significant amount of aerosol in the tropical lower stratophere.

shown in Fig. 3. Tropical cirrus showed a depolarization of 20%. Cirrus clouds measured with the same instrument at midlatitudes [12] exhibit a wide range of depolarization ranging from almost zero up to 80%. This is due to the great variety of sizes and shapes that the cloud particles may come in.

The wavelength dependence of the backscatter coefficients determined at 532 and 355 nm with the lidar shows a slight enhancement of the blue color for the tropical clouds. Usually, cirrus scatter equally strong at these two wavelength. These wavelength dependence of the TC indicate small particles with radiuses in the range of some µm.

Acknowledgments. We would like to thank I. Beninga and W. Ruhe (Impres GmbH.) as well as T. Ronge for their support in performing the measurements.

REFERENCES:

1. McFarquhar G.M et al. Thin and Subvisual Tropopause Tropical Cirrus: Observations and Radiative Impact, *J. Atmos. Sci.*, 57, 1841-1853, 2000
2. Boehm M. T. et al. On the maintenance of high tropical cirrus, *J. Geophys. Res.*, 104, D20, 24,423-24,433, 1999.
3. Jensen E. and Pfister L.,Transport and freeze-drying in the tropical tropopause layer, *J. Geophys. Res.*, 109, D2, 10.1029/2003JD004022, 2004.
4. Klett J.D, Lidar inversion with variable backscatter/extinction ratios, *Appl. Opt., 24*, 1638-1643, 1985.
5. Beyerle G., M.R. et al. 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.
6. Goldfarb L. et al., Cirrus Climatological Results from Lidar Measurements at OHP (44°N, 6°E), *Geophys. Res. Lett.*, 28, 1687-1690, 2001.
7. Peter, T, Ultrathin Subvisible Cirrus Clouds at the Tropical Tropopaus, *AIP conf. proc.*, 534, 619-622, 2000.
8. Sassen K. et al. Optical Scattering and microphysical Properties of Subvisual Cirrus Clouds and Climatic Implications, *J. Appl. Meteor.*, 28, 91-98, 1989.
9. Wang P.-H. et al. 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.
10. Bauman J. J. et al. A stratospheric aerosol climatology from SAGE II and CLAES measurements: 2. Results and comparisons, 1984–1999, *J. Geophys. Res.*, 108, D13, 4383, 10.1029/2002JD002993, 2003 .
11. Immler F., O. Schrems,Lidar measurements of cirrus clouds in the northern and southern hemisphere during INCA (55°N, 53°S): A comparative study, *Geophys. Res. Lett.*, 29, 16, 10.1029/2002GL015077, 2002.
12. Immler F. and O. Schrems Determination of tropical cirrus properties by simultanious Lidar and radiosonde measurements, *Geophys. Res. Lett.*, 29, 23, 10.1029/2002GL015076, 2002.