LIDAR OBSERVATIONS OF EXTREMELY THIN CLOUDS AT THE TROPICAL TROPOPAUSE

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ABSTRACT:

Our two lidar systems MARL (Mobile Aerosol Raman Lidar) and ComCAL (Compact Cloud and Aerosol Lidar) have been operated during measurement campaigns aboard the research vessel Polarstern (2003 and 2005) and at Paramaribo/Suriname (5.8°N, 55°W) in 2004/2005. The lidar systems detect cirrus in the upper troposphere with a very high sensitivity by the depolarization measurement. Cirrus properties like altitude, optical depth, particle phase are derived from the lidar signals. Using scattering theory and an estimate of the particle size, the number concentration of ice particles can be calculated.

In almost 90% of the measurements performed at Paramaribo thin or subvisible cirrostratus were detected in the tropical transition layer (TTL). Occasionally, extremely thin clouds with optical depths below 10^{-4} were observed at the cold point tropopause (CPT). The condensed mass concentration was 0.5 µg/m^3. If we assume a particle size of 5 µm (effective radius) this corresponds to a number density of only a few particle per liter. The extremely thin clouds which were observed at - or even slightly above - the cold point tropopause seem to dwell in subsaturated air. Our findings indicate that these thin layers of particles, are not composed of pure water ice.

1. INTRODUCTION

The tropical tropopause is of particular interest in the global atmospheric circulation pattern since it is the only region where tropospheric air enters irreversibly the stratosphere. Already back in 1949 Brewer [1] described a stratospheric residual circulation ('Brewer-Dobson-Circulation) according to which air enters the stratosphere in the tropics, rises to high altitudes and drifts polewards, where it sinks and finally is mixed back into the troposphere. He also pointed out that the cold temperatures at the tropical tropopause are responsible for the low water concentration of water in the stratosphere, since the water is freeze-dried during the ascent .

However, Newell et al. [2] showed that even at the tropical tropopause the annual and zonal mean temperatures are too high to explain measured stratospheric water vapor mixing ratios. They suggested that air must cross the tropopause at times and locations where it is coldest, and identified the region of the maritime continent during northern hemispheric winter and the Bay of Bengal and India during northern hemispheric summer.

Reference Sherwood and Deshler [3] suggested that overshooting in strong convective cells feeds extremely dry air into the lower stratosphere, but it is doubtful whether overshooting does provide enough mass for the Brewer-Dobson circulation. Also, it is unclear whether convective overshooting is indeed an efficient mechanism for drying the TTL.

Recently, Fueglistaler et al. [4] showed that estimates of the water vapor mixing ratios of air entering the stratosphere based on trajectory calculations using operational analysis data are low enough to be in good agreement with measurements. In this study it is assumed that air is dried to the saturation vapor pressure at the coldest point of its trajectory. However, it is questionable if the freeze-drying process at the tropical tropopause can be so efficient. According to Heymsfield et al. [5], ice clouds require a significant supersaturation to form. Also, ice particles in the TTL are presumably rather small. Therefore, sedimentation is of limited efficiency for the dehydration air except for very small updraft velocities of the order of 1 mm/s.

In this study we provide lidar observations of thin ice cloud layers that occur frequently at the tropical tropopause.

2. INSTRUMENTAL

We are operating two mobile lidar systems MARL and ComCAL. The mobile aerosol Raman lidar (MARL) [6] is a backscatter lidar that uses a Continuum 9030 Nd:YAG laser which emits pulses at 532 nm and 355 nm with about 350 mJ of energy each into the atmosphere. A Cassegrain telescope with 1.1 m aperture collects the backscattered light which is then analyzed by a 10-channel polychromater. Light polarized parallel and perpendicular with respect to the polarization plane of the outgoing laser beam are measured in separate channels. The vibrational Raman scattering of nitrogen is detected at 607 nm and 387 nm as well as the Raman scattering from water vapor at 532 nm.

The second lidar system (Compact Cloud and Aerosol lidar (ComCAL) was recently build for routine measurements aboard the research vessel Polarstern and is described in detail in a companion paper [7].

The MARL system has performed measurements aboard the research vessel Polarstern in 1998 (Bremerhaven, Germany - Punta Quilla, Argentina), 2000 (Punta Arenas, Chile - Bremerhaven), and 2003 (Bremer-

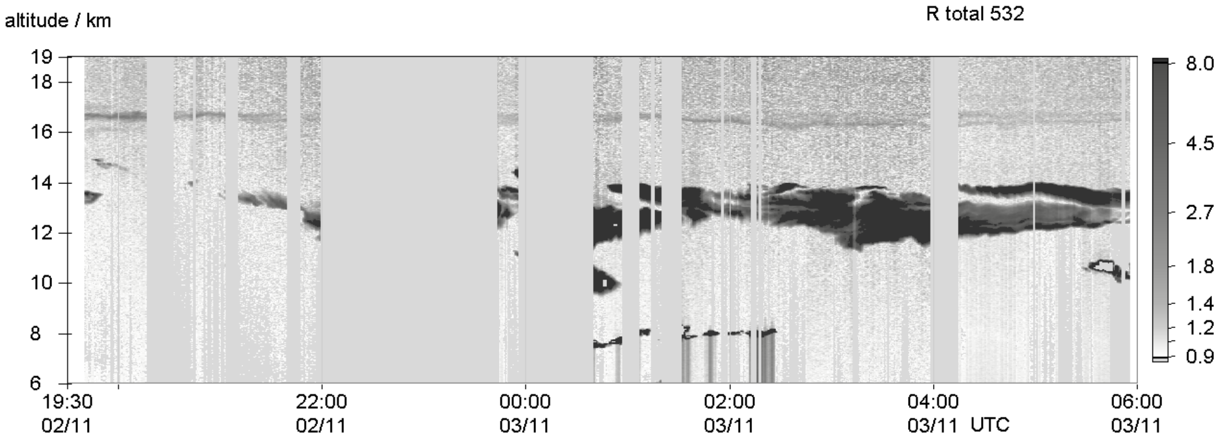

Fig. 1: Time series of measurements of the ComCAL instrument aboard Polarstern on 02 Nov 2005 around 9°N, 19°W.

haven - Cape Town, South Africa). Since fall 2004 the MARL system is based in Paramaribo, Suriname (5.8°N, 55.2°W) where it participated in the STAR pilot study and took measurements during the long dry season from 24 Sept 2004 to 16 Nov 2004 and during the subsequent short dry season from 22 Feb 2005 to 10 March 2005. ComCAL was operated aboard Polarstern during the cruise ANTXXIII/1 from Bremerhaven to Cape Town from 13 Oct 2005 to 17 Oct 2005.

3. OBSERVATIONS

During the STAR pilot study in Paramaribo cirrus in the upper troposphere were frequently observed. In 88% of all measurements ice particels were detected by enhanced backscatter and depolarization. A large fraction of about 40% of these clouds were subvisible, i.e. their optical depth was below 0.03. The lidar ratio of visible cirrus was determined using Raman signals. Tropical cirrus have lidar ratios of about 25, which is somewhat higher than what is observed in the midlatitudes. The typical values that were determined with the same instrument at 53°N were about 20. On top of the visible cirrus, extremely thin clouds were frequently observed in about 17 km altitude.

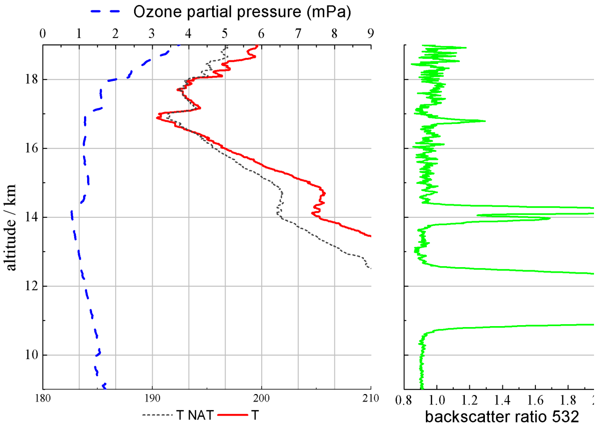

Fig. 2: Profile of the temperature (solid), the existence temperature for Nitric Acid Trihydrate (NAT) [8] using 0.3 ppb of HNO3 (dots) and the Ozone partial pressure (dashed) measured by a radiosonde which was launched on 03 Nov 2005 at 11:00 UT. The plot to the right shows the backscatter ratio measured at 8:47 UT.

During the Polarstern cruises the general picture was the very similar. Fig. 1 shows a time series of ComCAL measurements aboard Polarstern. Thick cirrus is observed between 12 km and 14 km. Well above these clouds a very stable layer of particles is detected at 16.4 km. The optical depth of this layer is about 0.001. The particle depolarization is 30%, meaning that these are solid particles of sufficient size in order to cause the strong depolarization (r >> l). A wavelengths dependence of the backscatter coefficients can not be determined with sufficient accuracy due to the low signal to noise ratio of this layer. If we assume that these were ice particles of a size that is typical for high altitude clouds in the tropics [9], which would be an effective radius r_{eff} of 5 µm, than the number density and mass concentration can be estimated from the returned signal applying Mie scattering theory.

In this particular case with a backscatter ratio of about 1.2, a concentration of 8 particles / liter is calculated. The ice water content of this cloud was about 2 $\mu g/m^3$ and the condensed water fraction was 0.5%. Fig. 2 shows the data of a radiosonde which was launched on 03 Nov 2003 11:00 UT form Polarstern, about two hours after the latest observation of this thin layer which was performed at 8:47 UT.

At 14 km the temperature sensor detected a strong inversion layer just above some thick cirrus clouds. These clouds form typically in the outflow from nearby convective systems. The extremely thin layers discussed earlier are found almost 3 km higher and are clearly separated from this convectivly formed clouds by the inversion. This observation suggest that the extremely thin cloud is not directly linked to the convec-

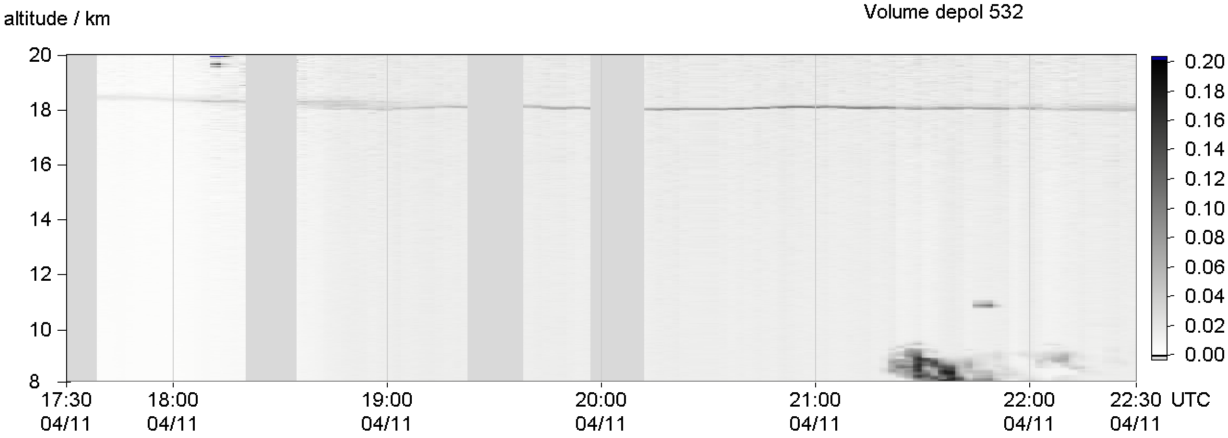

Fig. 3: Time series of a MARL depolarization measurements aboard Polarstern from 4 Nov 2003 at about 5°N, 15°W An extremely thin layer of particles was observed for 5 hours above 18 km altitude.

tion which is active in this area. The balloon launched from Polarstern on 3 Nov also carried an EEC ozone sonde. The ozone profile is shown in Fig. 2 along with the temperature profiles. The low values in the region between the inversion and the temperature minimum which is termed the tropical tropopause layer (TTL) indicate a tropospheric origin of this air. On the other hand the slight enhancement of the ozone values at the inversion again suggest that the air was not directly injected into the TTL by nearby thunderstorms. We therefore conclude that the particles at 17 km altitude are not a result of convective overshooting. It is more likely that they are formed in slow ascent.

A similar observation was made 2 years earlier with the MARL system aboard Polarstern. Fig. 3 shows a time series of measurements from 04 Nov 2003, when Polarstern was about 5° N, very close to the ITCZ. A layer of particles is detected that is basically not visible in the parallel backscatter signals. The reason for this is the higher contrast in the perpendicular channel, which is due to the low depolarization of the molecular return (ca. 1%) compared to the strong depolarization of solid particles. The backscatter ratio of the 532 nm cross polarized signal was about 4. Given a molecular backscatter coefficient of $2x10^{-7}\,m^{-1}$ and the just mentioned molecular depolarization ratio an backscatter coefficient on the order of $10^{-8}\,m^{-1}$ can be estimated for this cloud. The optical depth is below 10^{-4}. Assuming again ice particle with $r_{eff} = 5\ \mu m$ the number concentration was 2/liter, the ice water content $0.5\ \mu g/m^3$ and the condensed water fraction 0.2%.

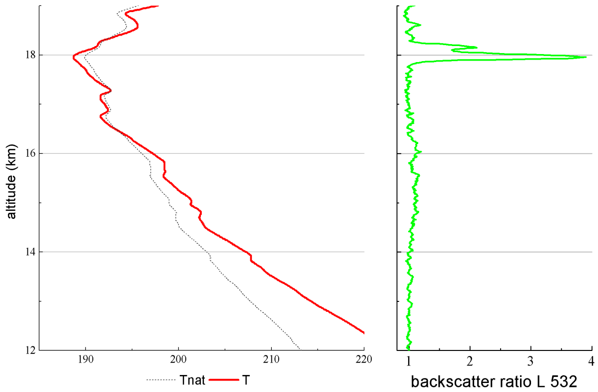

Fig. 4: Temperature profile (solid line of left graph), existence temperature of NAT (dots) measured by a radiosonde launched on 4 Nov 03 21:40 UT and perpendicular backscatter ratio measured by MARL on 4 Nov 03 as a 20 min mean from 22:50 to 23:10.

This cloud was about a factor of 5 less dense than the one discussed above (Fig. 1). However, the temperature profile shows some similarities to this case. Again there is a strong temperature inversion some kilometers below the cloud (Fig. 4). The temperature minimum is about 1 km higher in altitude, at 18 km, and is with 189 K somewhat colder than in Fig. 2 with 191 K. It is interesting to note that the cloud layer has two peaks, one is almost exactly at the cold point tropopause, the second one lies about 100 m above. The radiosonde was launched at 21:40 UT and reached the altitude of the cloud layer about 80 min later so there is a good temporal match between the two types of measurements. Given the stability of the layer that stayed for several hour at the same altitude, the drift of the sonde and the movement of the ship should not have a strong effect on the comparability of the data. Consequently, we have evidence, that there is a layer containing particles above the cold point tropopause.

3. CONCLUSIONS

The frequent observation of extremely thin layers of frozen particle layers at the cold point tropopause in the tropics is puzzling since these clouds contain only a very small fraction of the total water. Ice particles form

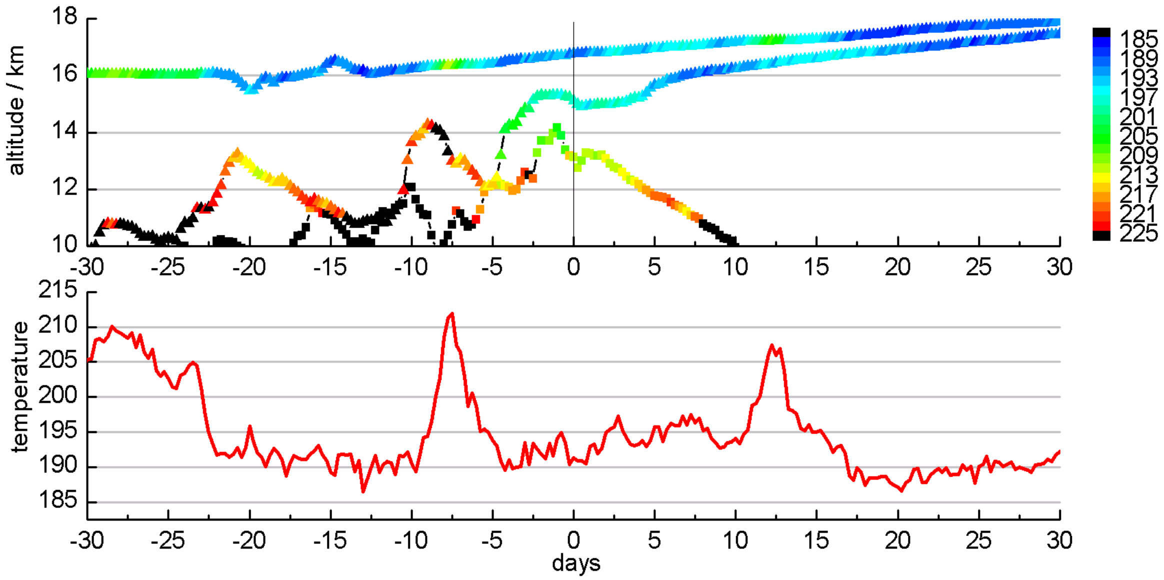

Fig. 5: Upper panel: back- and forward trajectories calculated for the location and time of the observation of Fig. 2. The lower panel depicts the temperature evolution of the uppermost trajectory of the upper plot..This trajectory corresponds to the the cloud layer observed by the lidar (Fig. 1)

only at supersaturations of 30% or more [5]. If thermal equilibrium is reached, this excess water should form ice in the cloud. Since the thin observed layers are very stable and last very long, it seems unrealistic that they exist that far from equilibrium. One mechanism that could explain this behavior was provided by Luo et al. [10]. However, the subtle balance between updraft and sedimentation needed for this mechanism requires the cloud to dwell below the CPT. We showed clearly, that in our examples this is not the case.

In order to study dynamic processes in the TTL in more detail we used a trajectory model that was recently developed at our institute [11]. Accordingly, the air parcel that contains the particle layer (the uppermost trajectory in Fig. 5) was slowly lofted during the past 2 weeks. The temperature history of this air indicates, that it had gone through several dehydration cycles already and therefore should be subsaturated. Fig. 2 shows the temperature profile along the existence temperature of nitric acid trihydrate (NAT) for a typical value of the concentration of HNO_3 for the TTL (0.3 ppb). The amount of NAT that could form under these conditions corresponds to the mass concentration of solid particles estimated from the backscattered signal of about $0.5 \mu g/m^3$. These findings let us conclude, that the extremely thin particle layers that were frequently observed at the tropical tropopause consist of NAT rather than ice.

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REFERENCES

1. Brewer, A. M.,, Q. J. R. Meteorol. Soc., 75, 351–363, 1949.

2. Newell, R. E., and S. Gould-Stewart , J. Atmos. Sci., 38, 2789– 2796, 1981.

3. Sherwood, S. C., and A. E. Dessler , On the control of stratospheric humidity, Geophys. Res. Lett., 27, 2513–2516, 2000.

4. Fueglistaler S., M. Bonazzola, P. H. Haynes, T. Peter, J. Geophys. Res., 110, D08107, 2005.

5. Heymsfield A. J. , L. M. Miloshevich, C. Twohy, G. Sachse, S. Oltmans, Geophys. Res. Lett., 25(9)., 1343-1346, 1998

6. Schäfer H.-J.,et al.., SPIE EurOpto Series 2581, 128-136, 1995

7. see: Immler et al. this issue.

8. Hanson D., K. Mauersberger, Geophys. Res. Lett., 15, 855-858, 1988

9. Heymsfield A.J., J. Atmos. Sci., 60(21)), 2573-2591, 2003

10. Luo B.P. et al., , Atmos. Chem. Phys.., 3, 1093-1100, 2003.

11. Tegtmeier S., Schoellhammer K., M. Rex, I. Wohltmann, J.-J. Morcrette, Poster presentation at 3rd SPARC General Assembly, 1-6 August 2004, Victoria, British Columbia,Canada, 2004.