Dehydration potential of ultrathin clouds at the tropical tropopause

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[1] We report on the first simultaneous *in situ* and remote measurements of subvisible cirrus in the uppermost tropical troposphere. The observed cirrus, called UTTCs (ultrathin tropical tropopause clouds), are the geometrically (200–300 m) and optically ($\tau \approx 10^{-4}$) thinnest large-scale clouds ever sampled ($\approx 10^5$ km^2). UTTCs consist of only a few ice particles per liter with mean radius ≈ 5 μm, containing only 1–5 % of the total water. Yet, brief adiabatic cooling events only 1–2 K below mean ambient temperature destabilize UTTCs, leading to large sedimenting particles ($r \approx 25$ μm). Due to their extreme altitude above 17 km and low particle number density, UTTCs may efficiently dehydrate air during its last encounter with the ice phase before entering the stratosphere. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 1655 Global Change: Water cycles (1836). **Citation:** Luo, B. P., et al., Dehydration potential of ultrathin clouds at the tropical tropopause, *Geophys. Res. Lett.*, *30*(11), 1557, doi:10.1029/2002GL016737, 2003.

1. Introduction

[2] Ice clouds in the vicinity of the tropical tropopause are responsible for the drying of air before troposphere-to-stratosphere transport. Despite the recognition of their crucial effect on the stratospheric water budget, neither the mechanisms of dehydration nor the relative importance of various cloud types are well understood. Three different hypotheses of tropical dehydration have been suggested: (i) freeze-drying of air during slow upwelling through the tropopause [*Brewer*, 1949] by large-scale formation of cirrus clouds either spanning the equatorial band or at distinct longitudes [*Newell and GouldSteward*, 1981; *Jensen et al.*, 1996; *Holton and Gettelman*, 2001]; (ii) convective overshooting in the turrets of cumulonimbus clouds leading to extreme cooling and subsequently to drying [*Danielsen*, 1982]; (iii) wave-induction of thin cirrus below [*Boehm and Verlinde*, 2000] or above [*Potter and Holton*, 1995] the tropopause.

[3] Recently space-borne aerosol lidar (light detection and ranging) observations of extended laminar clouds at the tropical tropopause [*Winker and Trepte*, 1998; *Omar and Gardner*, 2001] have directed scientific interest to very thin visible and subvisible cirrus. The few available *in situ* and remote sensing observations of such clouds [*McFarquhar et al.*, 2000] suggest optical depths $\tau \approx 10^{-3}$, i.e. a factor of 30 below visibility (0.03) [*Sassen et al.*, 1989], see Table 1. Here we report on even thinner cirrus observed during the APE-THESEO campaign, which was based on the Seychelles in the western Indian Ocean during Feb–Mar 1999, deploying the high-flying Russian research aircraft Geophysica carrying *in situ* instrumentation [*Stefanutti et al.*, 1999], and the German DLR Falcon equipped with the aerosol lidar OLEX [*Wirth and Renger*, 1996]. The Geophysica was maneuvered into the cirrus according to the instructions given by the lidar scientists aboard the 'pathfinding' Falcon, leading to the first concurrent *in situ* and remote measurements of such cirrus. We found extensive cirrus (>10^5 km^2), which were optically extremely thin ($\tau \approx 10^{-4}$) and remained invisible for the Geophysica pilot [*Luo et al.*, 2003; *Peter et al.*, 2003]. Due to their extreme altitude UTTCs are likely the final encounter with the ice phase before air ascends to the stratosphere, endorsing a dehydration potential crucial for the stratosphere.

2. Observations of UTTCs

[4] Figure 1A shows the total lidar backscatter ratio at 1064 nm wavelength (R_{1064}) from OLEX during a flight on

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Table 1. Properties of Tropical Cirrus Clouds as Observed or Modeled

Observations	cloud base (km)	thickness (km)	radius (μm)	# density (L^{-1})	condensed mixing ratio	$\tau \times 1000$	R_{1064}	R_{532}	occurrence frequency
McFarquhar et al. [2000]	16.1	0.7	$r_1 = 3^a$ $r_2 = 15.25$	$n_1 \sim 60$ $n_2 \sim 5$	1 ppmv	60	15	1.5	
McFarquhar et al. [2000]						0.1–1 1–10 10–100			6%[b] 67% 27%
Heymsfield andMcFarquhar [1996]	~12	2–3	~50		~8 ppmv				
Winker and Trepte [1998]	18.2	0.35				4		~3	14%
Omar and Gardner [2001]	13–15	1.2–5						>1.1	52%
Pfister et al. [2001]	15.2	2.3							~30%
Wang et al. [1998]	10–17	1–6				0.8–300			ns
Heymsfield [1986]	16.5, 17.5	0.5, 0.3							
This Work	16.9–17.4	0.2–0.3	~5	2–10	20–100 ppbv	0.1–0.5	2–5	1.05–1.2	31%
Models									
Boehm et al. [1999]	<16	1	5–10	100–10000	~30 ppmv				
Jensen et al. [2001]	15	2	17	~0.05	~10 ppbv	0.15	~1.05	~1.004	
This Work	16.9–17.	0.05–0.2[c]	~5	40–10[c]	200–50 ppbv[c]	~0.4	10–3[c]	~1.5–1.1[c]	

[a]*In situ* measurements of 2-mode cloud.
[b]Occurrence frequencies given by *McFarquhar et al.* [2000] are normalized to number of observations with clouds, while all other occurrence frequencies are normalized to all observations including clear sky measurements.
[c]The simulated cloud in Figure 2 is about a factor of 4 thinner than observed, but can be explained by stronger temperature fluctuations. ns = not specified.

27 Feb 1999. The aerosol depolarization ratio measured by OLEX at 532 nm is 10–30 % inside the UTTC, revealing that the particles are aspherical, presumably of crystalline nature. The black line indicates the flight path of Geophysica responding to guiding by the pathfinder. Figures 1B and C show *in situ* measurements of the sideways looking scatterometer MAS (R @ 532 nm) and the Ly-α hygrometer FISH, respectively. FISH measures the total water, i.e. gas phase concentration plus the particulate signal enhanced by about a factor of 5. Both measurements are strongly correlated with the Falcon lidar signal. The condensed H_2O derived from FISH yields about 60 ppbv of H_2O in the form of ice [*Peter et al.*, 2003]. Assuming the particles can be approximated as prolate ice spheroids with equivalent sphere radius of 5 μm, a lidar retrieval by means of T-matrix calculations [*Carslaw et al.*, 1998] shows that the very low backscatter ratios $R_{1064} \approx 1.2–3.5$ and $R_{532} < 1.2$ (cf. Figure 1B) correspond to ≈30 ppbv of condensed phase water [*Peter et al.*, 2003]. Upon encounter of a UTTC the FSSP-300 particle counter aboard the Geophysica shows a sudden increase in particle volume by more than 2 orders of magnitude [*Thomas et al.*, 2002], revealing a distinct particle mode around $r \approx 5–6$ μm.

[5] The small condensed mass of 30–60 ppbv H_2O within the UTTCs requires steady temperatures 0.11 K below the frost point, otherwise the clouds would evaporate or grow readily. *Luo et al.* [2003] suggest that the ice particles are remnants of thicker cirrus (as at 52°E in Figure 2A) kept stationary by mesoscale upwelling at a level where the ice saturation ratio crosses from supersaturation above to subsaturation below the cloud. Particles can stably oscillate about the altitude given by $S_{ice} = 1$: when particles happen to sink below this level entering a region of subsaturation, they start to evaporate, deposit water in the gas phase, become lighter, and the upwelling drives them back to the $S_{ice} = 1$ level; conversely, the air above is supersaturated, growth of the particles increases their weight, they deplete the gas phase, and they sediment back to the $S_{ice} = 1$ level.

[6] Of the total of 19 hours of OLEX in-flight observations, covering some 14000 km, 40 % showed only thicker cirrus (visible or subvisible), 19 % thicker cirrus and UTTCs, 12 % only UTTCs, and 29 % were clear sky [*Peter et al.*, 2003]. Hence, with an appearance of almost one third of the entire observation time UTTCs are a very frequent and stable phenomenon, in contrast to *McFarquhar et al.*

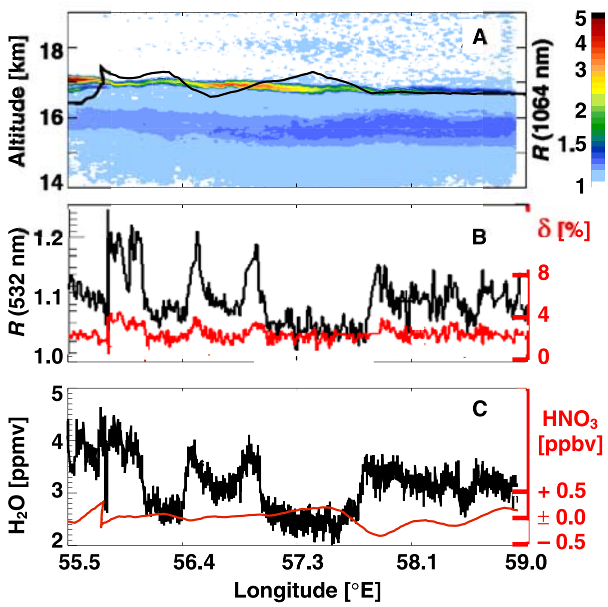

Figure 1. (A) Total lidar backscatter ratio at 1064 nm (R = 1–5) of a depolarizing 200–300 m thick UTTC at 17 km altitude observed by OLEX on the Falcon on 27 Feb 1999 (10°S, 4 UTC). Geophysica flight track is marked by black line. *In situ* measurements on board Geophysica of (B) backscatter ratio R (black curve) and volume depolarization δ (red curve) measured by the aerosol sonde MAS and of (C) total water measured by FISH (black curve) and particulate nitric acid measured by CVI-TDL (red curve).

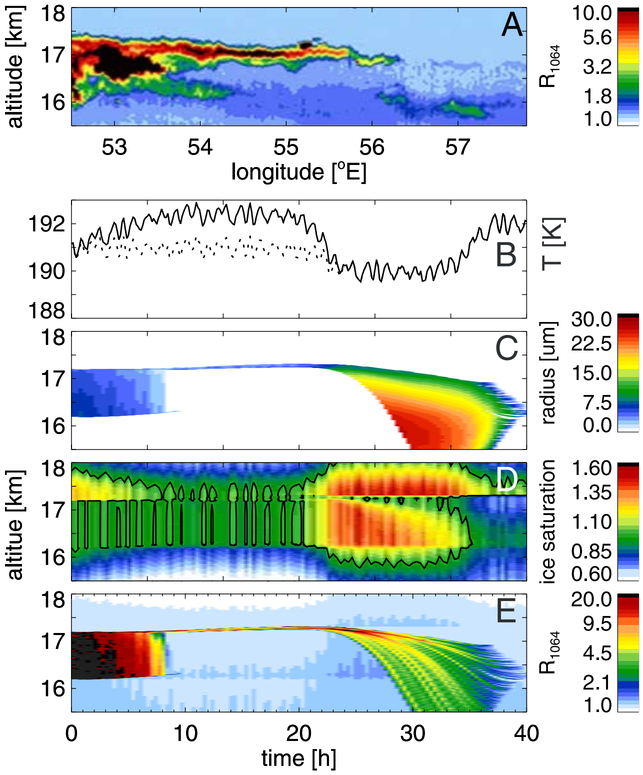

Figure 2. (A) Total lidar backscatter ratio (1064 nm) measured during the return flight leg on 27 Feb 1999. (B–E) Modeling of the 36-hr evolution of a cirrus balanced by upwelling. (B) Temperature at 17.3 km altitude (solid curve). The temperature fluctuation is the same for all the altitude levels. (C) Mean radius of ice particles, initially log-normally distributed. (D) Saturation ratio S with respect to ice, black contours show saturation ($S = 1$). (E) Backscatter ratio at 1064 nm from ice crystals assuming spheroidal prolate shape with aspect ratio 0.5.

[2000] who reported < 6 % of all clouds to have $\tau < 10^{-3}$ during 4 ER-2 flights in the central Pacific (Table 1).

3. Modeling and Discussion

[7] Figure 2A shows the same cloud as in Figure 1, now 1–2 hours later on a return flight leg. Results from a column model [*Luo et al.*, 2003] with 10-m altitude bins for the gas phase and a Lagrangian treatment of 5000 individual particles interacting with the gas phase are shown in Figures 2B–2E. The simulation starts with a 1-km thick cirrus, which might have nucleated in convective events, in gravity waves or in large scale upwelling similar to the cloud modeled by *Jensen et al.* [2001]. A slight warming (panel B) makes the cirrus evaporate, but leaves a UTTC at 17.3 km behind, because the air remains slightly supersaturated above this altitude (D). Between 8 hr and 24 hr particle radii (C) and number densities (not shown) are similar to those measured inside the UTTCs. The backscatter ratio R_{1064} (panel E) shows that in addition to the UTTC a moist layer is left at the lower edge of the original cirrus leading to water uptake by the H_2SO_4-H_2O background droplets. There is a similar feature, i.e. a non-depolarizing layer around 16 km, in Figure 1A. To stabilize the UTTC, upwelling velocities of 5 mm/s are required just below the tropical tropopause, which is relatively large in the absence of moist convection. However, as outlined by [*Luo et al.*, 2003], such upwelling is consistent with heating rate calculations and radar vertical wind measurements close to the tropical tropopause, and with the ozone measurements onboard the Geophysica when one assumes a simple balance between upwelling and photochemical production of ozone above 15.5 km.

[8] The fate of a UTTC depends on the further temperature evolution. Ubiquitous gravity waves with up to ± 0.4 K [*Bacmeister et al.*, 1999] shift the equilibrium altitude, but the mechanism described above restabilizes the particles (fluctuations Figure 2B). Stronger warming (>2 K) removes the supersaturation, leading to complete evaporation. However, rapid adiabatic cooling, e.g. wave-driven, may destabilize the UTTC irreversibly with subsequent dehydration of the air directly below the tropical tropopause. Figure 2 shows the modeling of such a cooling event around 24 hr. The applied cooling by 2.5 K lowers the $S_{ice} = 1$ level to below 16 km (black curve in D), so that the particles fall freely into supersaturated space, grow to radii of 25 μm (C), and hence carry the equivalent of up to 1 ppmv H_2O. The sedimenting particles may be responsible for the larger particle mode observed by *McFarquhar et al.* [2000], see also in Table 1.

[9] The resulting dehydration is clearly visible in the modeling (Figure 3A). In the observation (Figure 2A), the thin depolarizing cirrus at 16 km altitude and 57°E is possibly left over from UTTC-induced dehydration. In this case, the ice particles originated from a UTTC, leaving dehydrated air behind as evidenced by the reduced aerosol backscatter above this cloud ($R_{1064} < 1.2$). A trajectory calculation based on ECMWF wind fields shows indeed rapid cooling (~1.4 K 6 hr prior to the observation of the UTTC near 57°E) associated with rising motion in this region [*Luo et al.*, 2003], which may have destabilized the UTTC particles, supporting the modeling results shown in Figures 2 and 3. According to the ECMWF-based trajectories the dehydrated air is then subject to troposphere-to-stratosphere transport. It must be emphasized that the temporal (6 hr) and vertical (≈ 1 km) resolution of the ECMWF data is not sufficient to study the motions of tropical air in

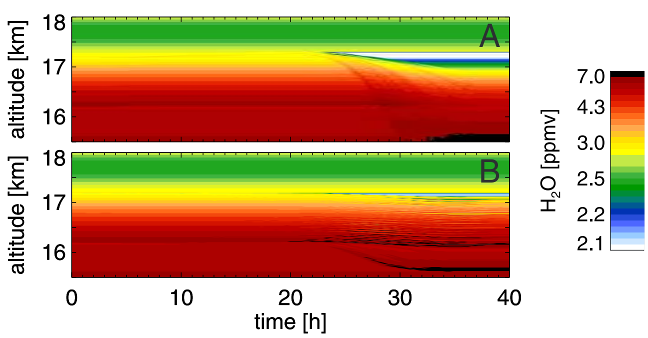

Figure 3. (A) Total water mixing ratio for the UTTC modeled in Figures 2B–2E. (B) Same, but for dehydration directly by the thicker cirrus shown in Figures 2C–2E following the temperature development shown by the dashed curve in Figure 2B.

great detail and that it is not clear how strongly the vertical motion field is influenced by shortcomings of the model parameterizations. UTTC-induced dehydration may be compared with dehydration via the sedimentation of thicker visible or subvisible cirrus clouds. If the initial cloud in Figure 2 is not evaporating but cooled directly (dotted temperature in 2B), the resulting water vapor profile (Figure 3B) shows much less efficient sedimentation at the upper cloud edge due to the higher ice particle number densities, which allow the particles to grow to smaller radii only.

[10] Based on the results in Figures 2 and 3 and assuming UTTCs to occur throughout the tropics we obtain a very rough estimate for the global mean dehydration induced by UTTCs

$$\Delta\chi \approx \Delta\chi_1 \times P_{\mathrm{coverage}} \times P_{\mathrm{collapse}} \times \left(\Delta z / V_{\mathrm{upwelling}}\right) / \Delta t,$$

where $\Delta\chi_1 \approx 0.5$ ppmv is the dehydration within a single UTTC encounter, $P_{\mathrm{coverage}} \approx 31$ % is the measured UTTC occurrence frequency in the tropics, $P_{\mathrm{collapse}} \approx 0.5$ is the chance for the UTTC to become destabilized in an adiabatic cooling event, $\Delta z \gtrsim 1$ km is the layer of air below the UTTC, which becomes supersaturated in the cooling event, $\overline{V}_{\mathrm{upwelling.}} \approx 1.3\mathrm{mm/s}$ is the mean upwelling velocity in the 1.5 km below UTTC altitude, and $\Delta\ t \lesssim 48$ h the typical UTTC lifetime. Upper and lower bounds for $\Delta\chi_1$ and $\Delta\ z$ are obtained from Figure 3, for $\Delta\ t$ from our observations. P_{collapse} assumes a brief cooling event to be as likely as a warming [*Luo et al.*, 2003]. 7000 ECMWF trajectories traveling from 360 to 380 K were used to average $V_{\mathrm{upwelling}}$. From this we obtain $\overline{\Delta\chi} \gtrsim 0.35$ppmv. Thus, in a global perspective UTTCs appear to play a major role in defining the last dehydrating step before air enters the stratosphere. Although this estimate suggests a large dehydration potential of UTTCs on the global scale, given the sparse data coverage in space and time the quantitative numbers obtained should be perceived with caution. A rigorous quantification of the UTTC dehydration potential in comparison with other mechanisms, e.g. dehydration in deep convection [*Danielsen*, 1982], remains a challenge.

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