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Unprecedented evidence for deep convection hydrating the tropical stratosphere

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[1] We report on in situ and remote sensing measurements of ice particles in the tropical stratosphere found during the Geophysica campaigns TROCCINOX and SCOUT-O3. We show that the deep convective systems penetrated the stratosphere and deposited ice particles at altitudes reaching 420 K potential temperature. These convective events had a hydrating effect on the lower tropical stratosphere due to evaporation of the ice particles. In contrast, there were no signs of convectively induced dehydration in the stratosphere. **Citation:** Corti, T., et al. (2008), Unprecedented evidence for deep convection hydrating the tropical stratosphere,

1. Introduction

[2] Air enters the stratosphere in the tropics [*Brewer*, 1949], where it is transported across the tropopause situated at about 380 K potential temperature (≈17 km) into the stratospheric overworld [*Holton et al.*, 1995] and toward higher latitudes in the Brewer-Dobson circulation. It is well known that moist boundary layer air is transported into the upper troposphere by deep convection with a main outflow region at about 13 km [*Folkins and Martin*, 2005]. How the air reaches the stratosphere is in contrast subject of ongoing debate. The way by which the rising air is dehydrated is closely linked to the transport mechanism of troposphere-to-stratosphere transport (TST) and equally uncertain.

[3] Two classes of hypotheses have emerged to explain dehydration. "Cold trap dehydration" assumes a large-scale upwelling motion as the main mechanism, involving quasi-horizontal transport through a "fountain" region over the maritime continent and Western Pacific, where the tropopause is particularly cold [*Newell and Gould-Stewart*, 1981; *Holton and Gettelman*, 2001]. The air is thereby gradually dehydrated in cirrus clouds. This hypothesis is supported by the distribution of high cirrus clouds [e.g., *Wang et al.*, 1996] and water vapor [*Read et al.*, 2004], by trajectory studies [*Jensen and Pfister*, 2004; *Fueglistaler et al.*, 2005] and radiative calculation [*Corti et al.*, 2006].

[4] The alternative hypothesis, "convective dehydration", postulates that dehydration occurs mainly in very deep, overshooting convection [e.g., *Danielsen*, 1993; *Sherwood and Dessler*, 2001]. This mechanism invokes overshooting to lead to extremely dry air caused by the extremely low temperatures in cumulonimbus turrets. However, efficient dehydration requires an air parcel to be exposed to these low temperatures for a sufficiently long time so that the ice particles can sediment out [*Holton and Gettelman*, 2001]. It is questionable whether convective overshoots satisfy this requirement. In contrast, model simulations suggest that overshooting convection has rather a hydrating than dehydrating effect [*Chaboureau et al.*, 2007; *Grosvenor et al.*, 2007].

[5] There are several reports on tropical deep convection reaching into the stratosphere [e.g., *Adler and Mack*, 1986; *Danielsen*, 1993] leaving open whether the air eventually mixed into the stratosphere or descended back into the troposphere. In addition, observations of ice above 380 K could not be linked unambiguously to convective overshoots [*Kelly et al.*, 1993; *Nielsen et al.*, 2007].

[6] The question whether deep convection leads to hydration or dehydration of the stratosphere is still open. The present study reports on in situ and remote observations of ice particles in the tropical stratosphere during two recent aircraft campaigns tackling two questions: Are the observed stratospheric ice particles of convective origin? If so, are these convective events hydrating or dehydrating the stratosphere?

2. Instruments and Data

[7] In 2005, two missions involving the high altitude research aircraft Geophysica [*Stefanutti et al.*, 1999] aimed at shedding light on these questions: the Tropical Convection, Cirrus, and Nitrogen Oxides Experiment (TROCCINOX) in the State of Sao Paulo, Brazil in February 2005 and the Stratosphere-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-O3) experi-

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Table 1. List of Flights on Which Ice Particles Have Been Observed in the Stratospheric Overworld (Above 380 K Potential Temperature) During TROCCINOX and SCOUT-O3: Date of Flight, Mean Geometric Altitude of 380 K (z_{380K}), Mean Relative Humidity Over Ice Between 380 and 400 K ($\overline{RHI}$), Total Ice Particle Observation Period Above 380 K (t^{ice}), Highest Geometric Altitude (z^{ice}_{max}), and Potential Temperature (θ^{ice}_{max}) of Ice Particle Observation

Date YYMMDD	z_{380K}, km	$\overline{RHI}$, %	t^{ice}, s	z^{ice}_{max}, km	(θ^{ice}_{max}) (K)
050204	17.0	66	172	18.0	(410)
050205	17.1	48	12	17.5	(387)
051119	17.8	74	121	18.2	(390)
051125	17.5	54	137	18.9	(415)
051129	17.5	65	477	18.2	(395)
051130	17.4	74	631	18.8	(417)

ment in Darwin, Australia, in November/December 2005 [*Vaughan et al.*, 2008].

[8] Here we use measurements of the following instruments on board Geophysica. Two instruments measure gas phase water and total water, the Fluorescent Airborne Stratospheric Hygrometer (FLASH) [*Sitnikov et al.*, 2007] and the Fast In situ Stratospheric Hygrometer (FISH) [*Zöger et al.*, 1999], respectively. Both instruments use the Lyman α fluorescence technique. The ice water content was calculated from the difference between these two instruments taking particle sampling enhancement into account. Cloud free periods were determined as the subset of measurements with water vapor concentrations from both instruments agreeing within ±20%. In addition, the following particle measurements were used to unambiguously determine the presence or absence of particulate water (auxiliary material).[1] The aerosol number density and size distribution from 0.27 to 1550 μm was measured using an FSSP-100 instrument in combination with a Cloud Imaging Probe (CIP). The Multiwavelength Aerosol laser Scatterometer (MAS) operates like a backscatter sonde and the Miniature Aerosol Lidar (MAL) [*Mitev et al.*, 2002] measures the profile of aerosol and cloud particles below the aircraft. Backscatter ratios are derived after applying a noise filter, range correction and correction for incomplete overlap in the near range, allowing observations as close as 40 meters from the aircraft. In situ temperature and pressure were measured with a Rosemount probe (TDC) at 1 Hz. During SCOUT-O3, vertical temperature profiles were obtained using the Microwave Temperature Profiler (MTP) [*Denning et al.*, 1989] with a resolution of about 13 seconds.

3. Observations

[9] During the TROCCINOX campaign, ice particles above 380 K were observed on two out of eight local flights, and during SCOUT-O3 on four out of eight. Table 1 lists the relevant flights and observed atmospheric properties. The total time during which ice particles have been encountered in the stratosphere (t^{ice}) amounts to about 25 minutes, with about 10 minutes of observations during the flight on 30 November 2005, which included the most extensive probing above the deep convective system "Hector" [*Vaughan et al.*, 2008].

[10] Figure 1 assembles the ice water content observations from all six flights. For better comparison, the figure layout is the same as that of *Kelly et al.* [1993, Figure 8b]. Figure 1 shows volume mixing ratios of particulate water corresponding to up to 50 ppmv at 400 K potential temperature and up to 5 ppmv at 415 K. This is considerably higher than the observation of less than 2 ppmv above 400 K by *Kelly et al.* [1993].

[11] Ice-particle-free water vapor observations in the stratospheric overworld are shown in Figure 2. The observed profile depicted in panel (a) is compact, except for several positive deviations, which were present on most flights. In contrast, no prominent negative deviations from the profile have been observed in the stratosphere. Panel (b) shows the distribution of deviations of water vapor ratios for all flights (auxiliary material).

[12] On all flights, the particulate water reported by the water vapor instruments is well correlated with the other particle measurements (Figure 3). Figure 3a depicts the temperature (blue) and potential temperature (red). The static pressure (not shown) was practically constant at 75 hPa. Figure 3b shows that the high total water concentrations (blue) due to the presence of ice particles coincide with the particle observations reported by FSSP (red) and elevated backscatter ratios by MAS (green). CIP (not shown) reported large particles with sizes of 40 μm and above, accounting for about half of the ice mass. With

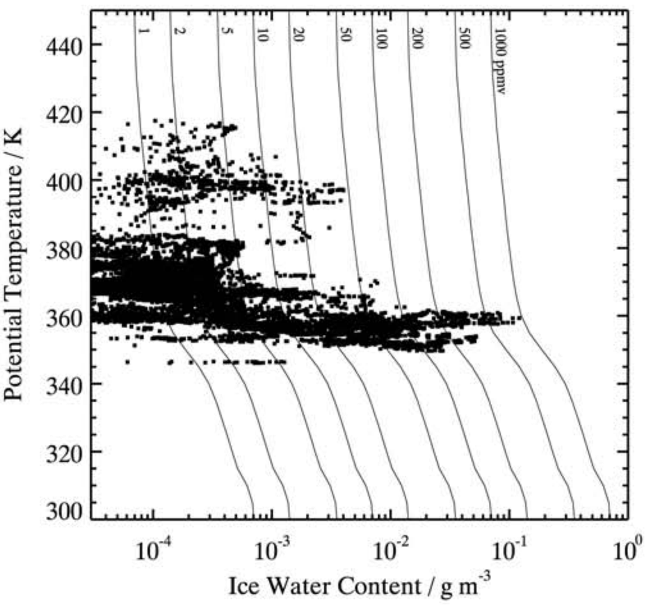

Figure 1. Ice water content derived from the measurements by the two water vapor instruments during all six flights listed in Table 1. The contours represent lines of constant volume mixing ratios calculated based on a mean air density profile. Observations suspected to stem from contrail sampling were excluded (see section 4.1).

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL033641.

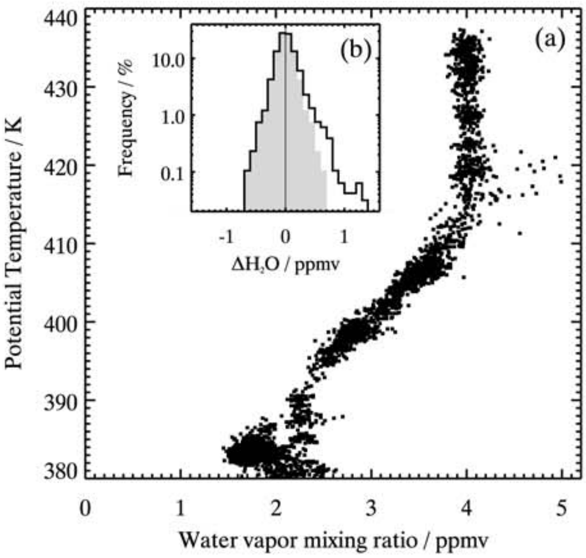

Figure 2. Stratospheric water vapor observations in air free of ice particles. (a) Observed vertical profile on 25 November 2005. (b) Probability distribution of water vapor mixing ratio deviations from mean profiles calculated from all flights listed in Table 1. The symmetric gray shading illustrates the distribution's skewness.

relative humidities between 60% and 70% with respect to ice, these particles are in the process of evaporation, but as they are relatively large they may survive for another hour. Finally, panel (c) shows the convective overshoot reaching the aircraft flight level.

4. Hypotheses for Observed Ice Particles

[13] There are three potential explanations for the stratospheric ice particles reported in the previous section: Unintended contrail sampling, in situ formation, or transport in deep convection.

4.1. Unintended Contrail Sampling

[14] During the TROCCINOX campaign, convective systems were overflown only once, excluding the possibility of measuring the aircraft's own exhaust. Conversely, the flight strategy for several flights during the SCOUT-O3 campaign included circling above deep convective systems, implying some likelihood of such artifacts. We evaluated the possibility of contrail sampling by analyzing the spreading and advection of Geophysica's contrail relative to the aircraft position at later times of the flights (auxiliary material).

[15] Applying this analysis to all flights revealed that during TROCCINOX, indeed none of the ice particles observed above 380 K could have originated from the aircraft exhaust. In contrast, during the SCOUT-O3 campaign, about 3% of the ice particle observations might stem from contrail sampling. These observations are excluded from Figure 1.

4.2. In Situ Formation

[16] Another explanation for the observed ice particles could be in situ nucleation and growth. Adiabatic cooling of air masses lifted above convective systems can lead to supersaturation, inducing the formation of so-called pileus clouds. This however requires supersaturation, which is contradicted by our observations. Rather, in all observed cases, the ice particles have been embedded in subsaturated air.

[17] Nevertheless, we have evaluated this hypothesis using a box model simulating the growth and sedimentation of ice particles, assuming a considerable supersaturation by fixing the relative humidity with respect to ice to 130%. Results from our calculations are summarized in Figure 4. The figure shows that nucleation at 19 km altitude and growth during several hours is needed to explain ice particles with a radius of about 40 μm at 17 km (lower trajectory). However, radar observations during both aircraft campaigns reveal that, in several cases, the convective systems formed only half an hour prior to the observation of ice particles above 380 K. It is therefore unrealistic to

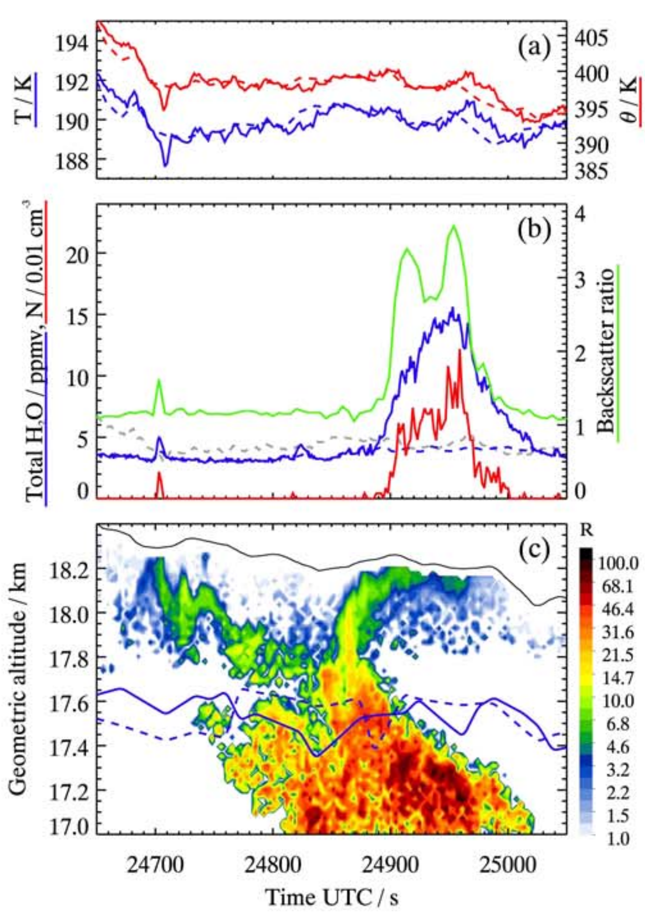

Figure 3. Stratosphere observed on 30 November 2005. (a) Temperature (blue) and potential temperature (red) from TDC (solid) and MTP (dashed) at aircraft altitude. (b) Total water (solid blue), gas phase water vapor (dashed blue), and water vapor saturation mixing ratio over ice in ppmv (dashed gray); FSSP particle number density ($r > 0.25$ μm) (red); MAS total backscatter ratio (green). (c) Backscatter ratio (R) from the downward looking lidar MAL (color-coded). Black curve: aircraft altitude. Blue solid and dashed curves: the 380 K and cold point tropopause, respectively, determined from MTP temperature profiles.

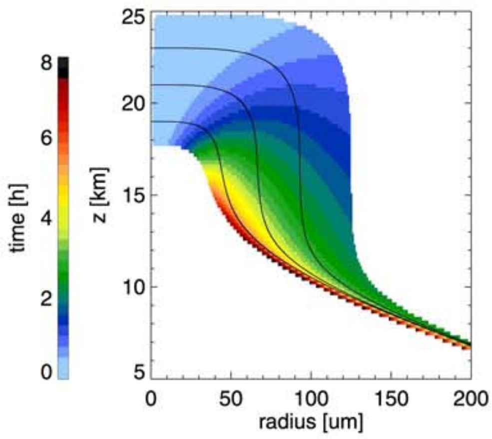

Figure 4. Growth and sedimentation of ice particles at 130% relative humidity with respect to ice. Trajectories of particles (black lines) that have nucleated on different altitudes. The colors indicate the time since nucleation.

assume that air above the convective systems was lifted substantially for more than an hour.

[18] Moreover, CIP reported particle sizes larger than 100 μm on several flights during the SCOUT-O3 campaign. Even if there had been 160% relative humidity over ice, such particles would require several hours to grow and would have to have formed above 20 km, because of their high fall speeds. Therefore, the observed ice particles cannot have formed in situ.

4.3. Deep Convection

[19] After having excluded the other two potential explanations, we are left with the third: Deep convection penetrating the tropical stratosphere. The most direct evidence for convective activity is given by the lidar observations presented in Figure 3c, showing the remnants of a convective plume.

[20] We conclude that convective transport is the sole possible explanation for most of the ice particles observed in the stratospheric overworld. As to the effect of these ice particles on the stratospheric water vapor content, Figure 2b suggests that their evaporation had a moistening effect. In contrast, there are no indications of "convective dehydration" in the stratosphere, i.e., no anomalously low water vapor mixing ratios were found.

5. Conclusion

[21] We have provided clear evidence of convection penetrating the tropical stratosphere. Due to evaporation of the ice particles, the observed events have a hydrating effect on the lower tropical stratosphere. Part of the observed ice particles might sediment back into the troposphere, limiting the magnitude of increase in stratospheric water vapor. In contrast, no signs of "convective dehydration" could be detected. A quantitative estimate of the impact of convective transport on the stratospheric water vapor content remains a challenge and will require further studies.

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