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Reply to comment by A. E. Dessler and E. M. Weinstock on “Balloon-borne observations of water vapor and ozone in the tropical upper troposphere and lower stratosphere” by H. Vömel et al.

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INDEX TERMS: 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; **KEYWORDS:** tropical tropopause, dehydration, stratospheric water vapor, upper troposphere, relative humidity, stratosphere troposphere exchange

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1. Introduction

[1] Vömel et al. [2002] (hereinafter referred to as V02) identified three different processes, which they called convective dehydration, nonconvective dehydration, and wave-driven dehydration. In addition, the absence of dehydration in some equatorial regions was pointed out. The first process of convective dehydration has been well studied [e.g., Danielsen, 1982, 1993; Vömel et al., 1995b]. In this process, air is lifted rapidly from the surface to the tropical tropopause and freeze-dried along the way. Additional dehydration may follow as a result of this process [Danielsen, 1982, 1993] but was not distinguished by V02. The identifying signature of this process is low ozone concentrations at the tropopause, indicating the recent boundary layer origin and saturation throughout the upper troposphere. The second process, nonconvective dehydration, dries air at the tropical tropopause most likely through slow ascent. This air has not recently ascended from the lower troposphere, as indicated by high ozone concentrations. The third process is related to wave events at the tropical tropopause. Here, dehydration occurs through the passing of Kelvin wave events [Fujiwara et al., 2001], which, over a timescale of several days, induce vertical motions at the tropopause together with temperature oscillations, which

can produce ice particles at their cold point [Boehm and Verlinde, 2000] and dehydrate air.

[2] These processes occur in different tropical regions. For completeness, V02 presented observations of regions that show no saturation and therefore no dehydration at the tropopause.

2. Presence of Ice Particles

[3] Whether the observations by V02 can distinguish between these different mechanisms hinges on whether the observations of saturation can imply the presence of ice particles. This assumption has been discussed by V02 in section 3.1 and will not be repeated here. Dessler and Weinstock [2003] point out correctly that saturation cannot always imply the presence of ice particles. However, widespread upper troposphere cirrus [e.g., Wang et al., 1996; Winker and Trepte, 1998] indicates that in the real atmosphere this assumption may be valid for significant portions of the equatorial tropopause region. Furthermore, the extremely cold tropopause temperatures, which are regularly observed in the eastern Pacific at San Cristóbal (see Figure 5 of V02), strongly suggest that the observations by V02 are not isolated events, but rather a regular phenomenon.

3. Lifetime of Ice Particles

[4] Dessler and Weinstock [2003] also point out that the lifetime of ice particles needs to be long enough for particles to sediment out. In their example, gravity waves with periods of 1–2 hours may not last long enough for these particles to sediment. The nonconvective dehydration mechanism, however, assumes that cold temperatures last significantly longer than 1–2 hours. Under these conditions, particles would form through slow cooling with growth of fewer and larger particles. The timescale would also be

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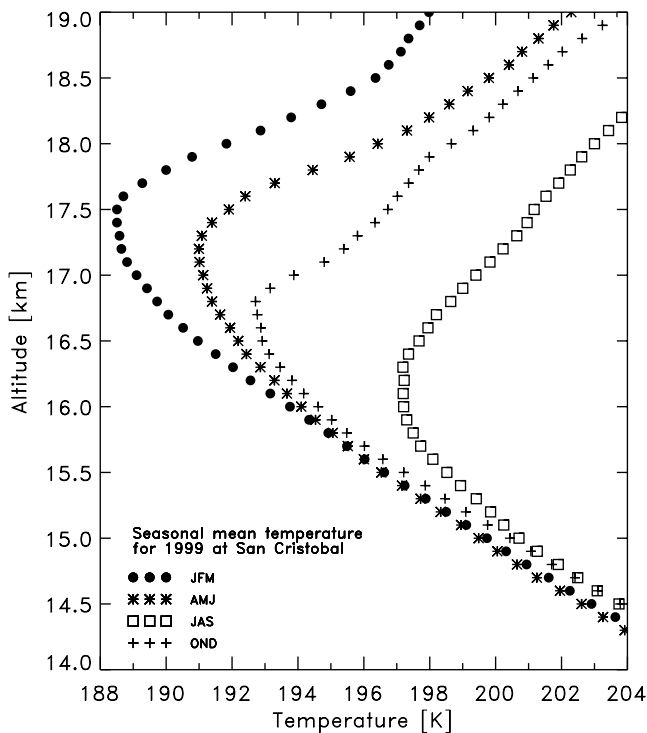


Figure 1. Seasonal mean temperature profile at San Cristóbal, Galapagos, from routine radiosonde profiles.

sufficient for particles to sediment a significant distance. For example, the average cold-point temperature at San Cristóbal, Galapagos, during the first three months of 1999 was 188.5 K (Figure 1) with an average saturation mixing ratio of 3.1 ppmv. Since this average is comparable to cold point saturation mixing ratios in the western Pacific and well below the mean stratospheric water vapor mixing ratio, we can assume that the observed saturation with peak values between 110% and 150% relative humidity over ice in each sounding was not a short event. Rather these observations show that cold saturated conditions may last for several days or longer. This may reflect a tropopause cold trap region similar to that described by *Holton and Gettelman* [2001] for the western Pacific.

4. Measurement Uncertainty

[5] The uncertainty of the water vapor measurement has been clearly stated by V02. According to the manufacturer, the uncertainty of Vaisala RS-80 temperature measurement using the appropriate radiation correction is 0.2°C and significantly less than the uncertainty assumed by *Dessler and Weinstock* [2003]. A number of dual RS-80 soundings show that at least the repeatability between two different temperature sensors is equal to or better than this uncertainty. Combining the uncertainty of 0.5°C in frost point temperature (which corresponds to about 10% uncertainty in mixing ratio; *Vömel et al.* [1995a]) with the uncertainty in ambient temperature leads to a total uncertainty in relative humidity of about 11%, which is about half of what *Dessler and Weinstock* calculated with their assumed temperature uncertainty. Intercomparisons with other in situ instruments cannot be used to specify the measurement uncertainty of

the frost point hygrometer, since none of the other in situ instruments can be considered a reference instrument. Furthermore, lab experiments have not shown any difference between the instruments referred to by *Dessler and Weinstock* [Kley *et al.*, 2000]; thus the disagreements between different aircraft instruments and between aircraft and balloon instruments observed in atmospheric measurements [Kley *et al.*, 2000] are not applicable to the discussion here. Furthermore, had V02 considered these differences, the frequency and the level of saturation would have been higher than what they reported, not lower, thus strengthening their argument, since higher values of supersaturation would make the formation of particles more likely. However, at the relative humidity peak values of 150% observed by V02, particle formation is likely and not a question of measurement accuracy.

5. Follow-up

[6] In response to further comments of *Dessler and Weinstock* [2003], based on this reply, the following points should be made:

1. Air clearly moves along the tropopause region and moves through regions of warmer and colder temperatures. The temperatures observed at San Cristóbal cannot be thought of as point temperatures, but rather as representative for a larger area. National Centers for Environmental Prediction analyses show that persistent, large-scale structures in the equatorial tropopause temperature are of the order of a few thousand kilometers or more. With typical wind speeds of several m/s the transit time is a few days to weeks. Lagrangian calculations such as those by *Holton and Gettelman* [2001] show that dehydration may be achieved in the transit of such cold regions. It is obvious that long-lasting cold regions can dehydrate more air than short cold events. V02 point out that the eastern Pacific region, which is generally considered a warmer region, can exhibit temperatures cold enough to contribute to dehydration in the tropical tropopause region.

2. *Dessler and Weinstock* [2003] are correct that the uncertainty of the relative humidity measurement is a minor point. In the context of the results of V02 it can be considered irrelevant. V02 frequently observed relative humidity peak values of up to 150%, which are unambiguously supersaturated even using the uncertainties of *Dessler and Weinstock*. We believe that the uncertainties in the measurements are clearly stated in V02 and are pleased to be able to expand on that discussion in this reply.

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