

## New evidence for the stratospheric dehydration mechanism in the equatorial Pacific

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**Abstract.** Water vapor profile measurements obtained in the western and central Pacific during the Central Equatorial Pacific Experiment (CEPEX) show a strong connection between the water vapor content near the tropopause and areas of deep convection. We show that air ascending within deep convective towers can be dried to mixing ratios below 1 part per million by volume (ppmv), which is much lower than the average mixing ratio observed in the stratosphere. A sharp increase of water vapor mixing ratio above the tropopause is an indication of the evaporation of ice particles at the top of deep convective cells. A mixed layer of up to around 1 km thickness above the tropopause in the regions of deep convection is indicated by the vertical profiles of ozone, water vapor, and potential temperature. Furthermore, a local maximum was observed at 20 km, which is an indication for the seasonal cycle of the tropopause temperature.

### Introduction

The tropics are believed to be the most important region for transport of tropospheric air into the stratosphere and for the drying of the stratosphere [Brewer, 1949]. The mean tropopause temperature in the warm pool of the western Pacific, particularly in the months November through March is cold enough to dry air to values of less than 3.5 ppmv [Newell and Gould-Stewart, 1981], which is required to explain the dryness seen in much of the lower stratosphere. Few in situ measurements of stratospheric water vapor have been done in tropical regions and the connection between the tropopause temperature and the mean stratospheric water vapor mixing ratio has not yet been well established. Observations in Brazil [Kley *et al.*, 1979], and Panama [Kley *et al.*, 1982] showed a water vapor minimum above the local tropopause, which they called hygropause. In their study they found that the hygropause could have not been created by local drying and concluded that it had been created somewhere else, presumably over the western Pacific. Data from Darwin during STEP [Kelly *et al.*, 1993] in January and February of 1987 confirm this idea and show that over northern Australia the tropopause and the hygropause are identical. They also note that the minimum saturation mixing ratio is lower than the mean stratospheric water vapor mixing ratio. However, the exact mechanism, that controls the stratospheric dryness has not yet been established, and several competing mechanisms have been proposed [Danielsen, 1982, and 1993, Newell and Gould-Stewart, 1981, Potter and Holton, 1995]

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### Measurements

Here we present data which were taken during the Central Equatorial Pacific Experiment (CEPEX) in March of 1993. In our study we obtained 8 water vapor and 17 ozone profiles from the research vessel Vickers between 160°E and 159°W mostly along 2°S and another 5 water vapor and 10 ozone profiles at Christmas Island (157.2°W, 1.5°N). Water vapor was measured using frost-point hygrometers [Oltmans, 1985, Vömel *et al.*, 1995], which have a long and successful record for soundings over Boulder and various other places. In this experiment, however, some of the water vapor soundings experienced interference with the radio transmitter on the payload, which was a result of combining water vapor and ozone sondes on the same payload. This interference created an altitude independent offset of the entire profile. These profiles were corrected using data at one stratospheric level from the HALOE instrument on the Upper Atmospheric Research Satellite (UARS) [J. Russell *III.*, personal communication, 1995]. Independent measurements in Boulder have shown a good agreement between these two instruments [Harris, *et al.*, 1995], as do the unaffected soundings of this study. By determining the offset at this level for each of the affected soundings, we could adjust the entire profile of the affected soundings from the surface to ceiling altitude. We estimate the accuracy in water vapor mixing ratio to be between 10% for the unaffected and 20% for the corrected soundings. Ozone was measured with a digital version of an electrochemical concentration cell (ECC) sensor. Since tropospheric ozone in the remote equatorial Pacific has very low concentrations and a sufficiently long lifetime, it is well suited as a tracer to distinguish tropospheric and stratospheric air and to detect recent events of deep convection, which transport ozone poor air up to the tropopause.

### Results and Discussion

The influence of deep convection on the water vapor content at the tropopause is shown in figure 1. As the air rises in deep convective towers it is cooled, and water vapor is frozen out. Most ice particles settle out, and thus remove water effectively from the air, leaving the local vapor density at saturation [Knollenberg *et al.*, 1993]. The dryness achieved at the top of the convection strongly depends on the temperature, and therefore the altitude the convection reaches. In the western Pacific, where deep convection reached a high tropopause, we observed the lowest water vapor concentrations. Figure 1a shows a mixing ratio of about 0.7 ppmv at the tropopause.

At Christmas Island the observed convection never reached as high, and the tropopause was significantly warmer and wetter, showing more structure compared to the western Pacific (figure 1b). The hygropause in this sounding was located about 1 km above the tropopause and was almost 1 ppmv dryer than the tropopause. Just above the tropopause this sounding shows a sharp local maximum in water vapor, and the temperature shows saturation up to this maximum. This peak just at the top of the

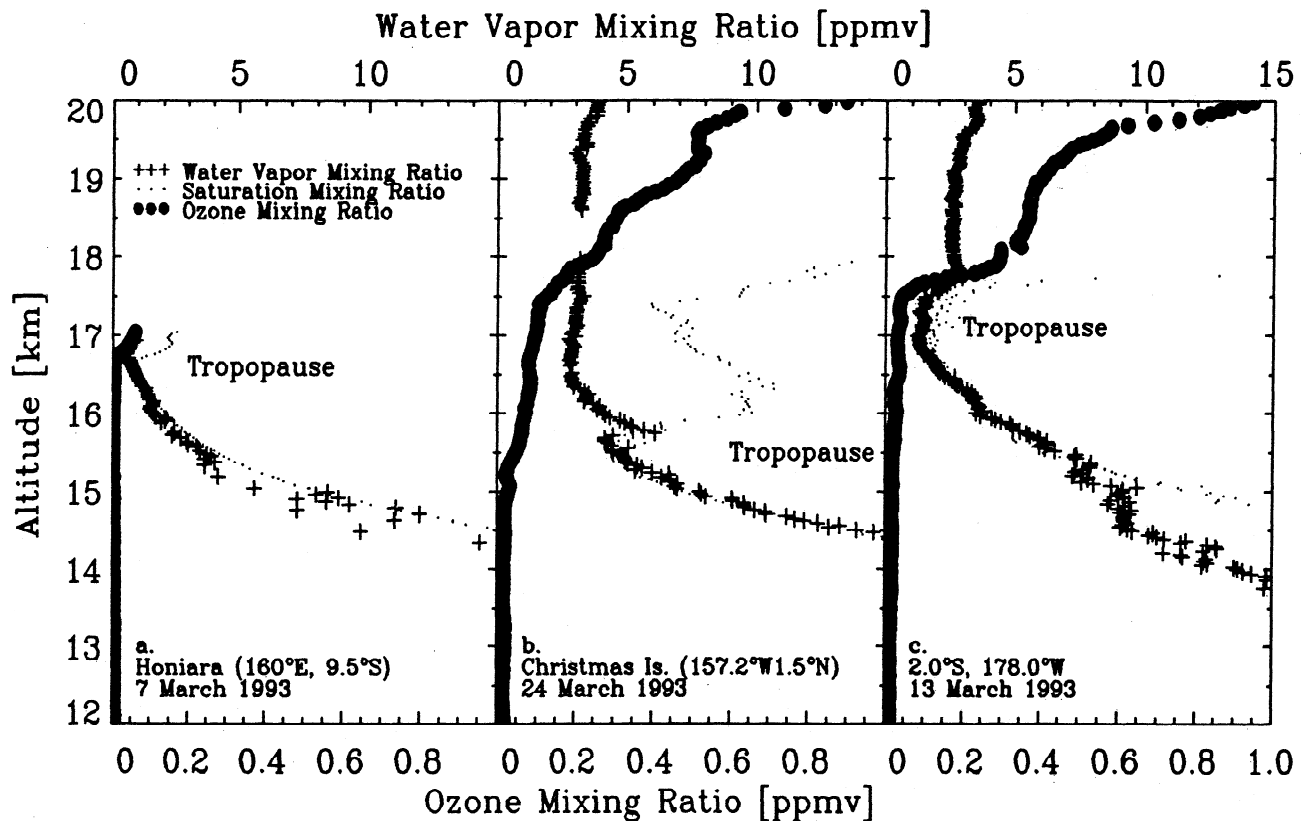


Figure 1. (a) Nearly saturated air and extremely low ozone concentrations extending up to the tropopause close to a deep convective event in the western Pacific. (b) Saturation but slightly higher ozone concentrations close to deep convection but reaching a lower altitude at Christmas Island. This profile shows clear indications for the evaporation of particles. (c) Same as in (a), in the outflow of deep convection in the western Pacific. This profile also shows indications for the evaporation of particles.

saturated region could therefore have been formed by the evaporation of ice particles, which were mixed into dryer and warmer air at the top of the deep convective layer. Data on ice particles, however, have not been available. Horizontal transport, on the other hand, seems to be insufficient to explain this peak, since it would require an additional mechanism, which cools the air to saturation. In the western Pacific we observed a sharp increase in water vapor directly above the tropopause (e. g. figure 1c). In this sounding we also found a local peak at the top of this increase, which again could be explained by the evaporation of ice particles at the ceiling of the convection. Since in this case the deep convection reached almost 2 km higher than at Christmas Island, the tropopause is much dryer and identical to the hygropause. The evaporation of particles could also explain, why this extreme dryness is not found anywhere else in the stratosphere. We observed this type of profile in 5 consecutive water vapor soundings in the western Pacific, where ozone, potential temperature, and water vapor profiles indicated that the air had been processed by deep convection.

In the western Pacific, in a region between roughly 18 and 19 km we frequently found layers of fairly homogeneous water vapor and ozone concentrations (e. g. figure 2). This would indicate a vertically mixed layer except for the fact that the potential temperature is slightly increasing. In a well mixed layer the potential temperature would remain constant. However, the gradient in potential temperature is significantly less compared to the sharp gradient at the tropopause or to the gradient above 20 km. This indicates that vertical mixing within this layer is still significant and comparable in time scales to diabatic heating. Mixed

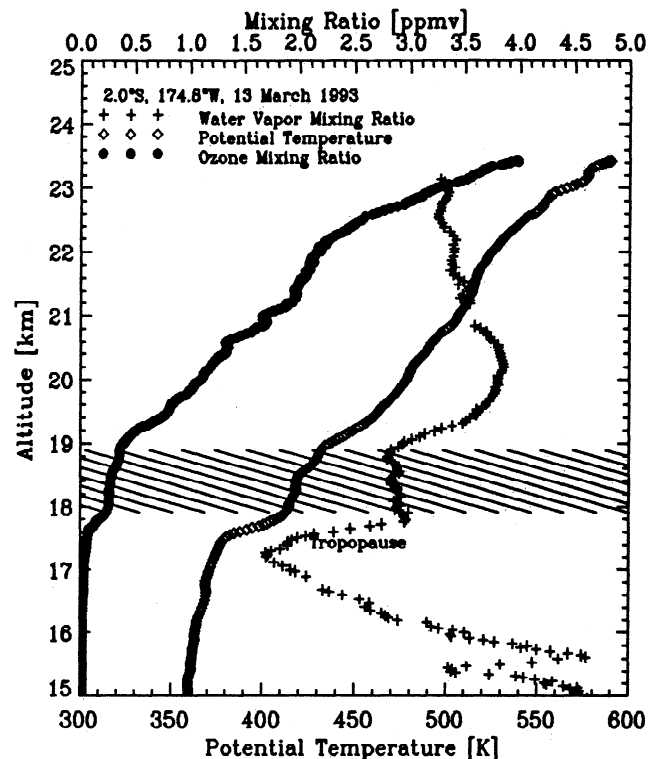


Figure 2. Indications for a nearly mixed layer (shaded region) in the profiles of water vapor, ozone, and potential temperature.

layers of this kind, but with variable extent, were encountered in over half of the soundings during the Vickers cruise. Data from STEP [Kelly *et al.*, 1993] indicated the presence of a layer of this kind as well. These layers, however, were rarely observed at Christmas Island.

Another important result is the presence of a broad local maximum in water vapor at 20.5 km (e. g. figure 3). This result was shown by all our soundings and has been confirmed by HALOE measurements [J. Russell, private communication, 1995] as well as aircraft data [K. Kelly, private communication, 1994]. In the picture of the general stratospheric circulation air enters the stratosphere and rises mainly in the tropics, driven by radiative heating. Mote *et al.* [1995] concluded that if latitudinal mixing is weak, the rising air would retain the water vapor concentration it achieved when it passed the tropopause, thus retaining the information about the mean tropopause temperature. The seasonal modulation of the mean tropopause temperature would then lead to a vertical modulation in the water vapor profile. Model calculations, and MLS data from their study show that a local maximum in water vapor should be found during CEPEX around 21 km, which is in good agreement with our observations.

**Conclusions**

The stratospheric dryness is not solely controlled by the lowest temperatures the tropopause can reach in the western Pacific, since in no place in the stratosphere did we observe the extreme dryness of the tropopause in the western Pacific. The indication of the evaporation of particles above the tropopause could explain this discrepancy at least in part. The combination of extreme dryness at the tropopause caused by deep convection reaching the tropopause and rehydration by evaporating particles seems to determine the water vapor content above the tropopause in the western Pacific.

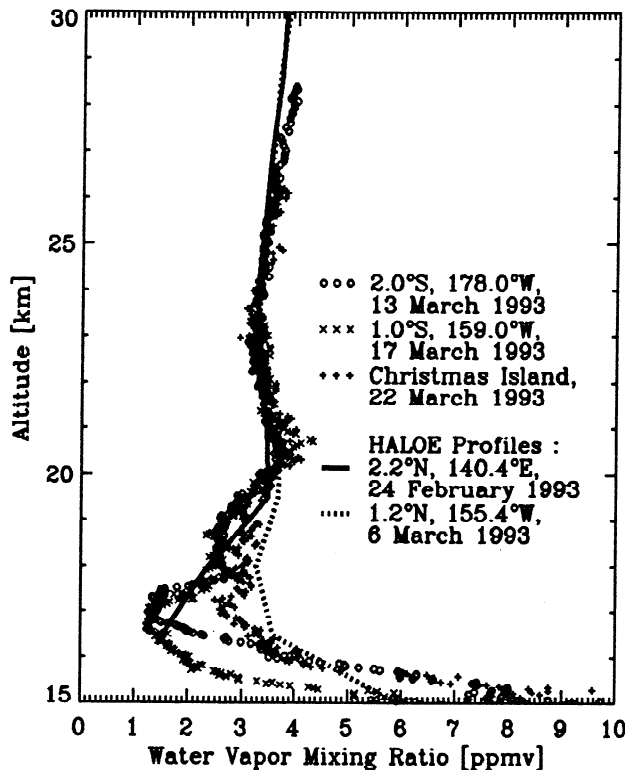


Figure 3. Seasonal, local maximum at 20.5 km shown by our balloon soundings as well as by HALOE.

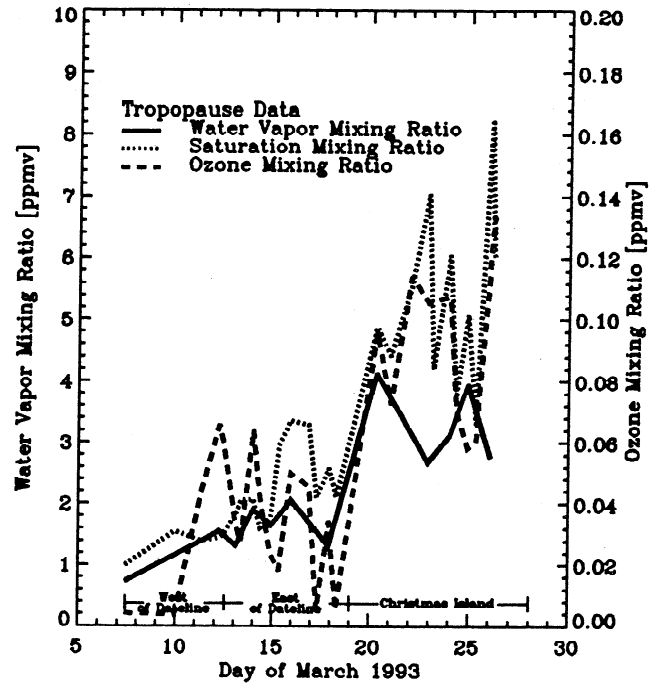


Figure 4. The effect of deep convection in the western Pacific and its absence at Christmas Island on water vapor, saturation mixing ratio, and ozone at the tropopause level.

In the central Pacific and over Christmas Island deep convection did not reach the same altitudes and levels of dryness. There we observed higher water vapor concentrations at the tropopause and in the 17 to 19 km region as well as increased ozone concentrations at the tropopause and below (figure 4). Horizontal and downward transport from subtropical regions as indicated by trajectory calculations is the likely cause of this observation as well as slow diabatic mixing across the tropopause. Above 20 km our data show no difference between the western and the central Pacific.

The seasonal maximum at 20.5 km, which has been described by Mote *et al.* [1995], shows that the equatorial lower stratosphere can retain the information about the mean tropopause temperature for a long time, which restricts the time scales for meridional mixing.

Compared to the STEP mission our data show a close similarity only to the observations during cyclones (Damien). We observed these features over a very large region of the western Pacific indicating that the ascent of extremely dry air, which may be rehydrated by evaporating particles or small scale mixing, controls the water vapor content of the lower equatorial stratosphere.

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