4.2.4. LONGITUDINAL AND TEMPORAL DISTRIBUTION OF DEHYDRATION IN THE TROPICAL TROPOPAUSE REGION

Balloonborne observations of frost-point temperature and ozone at several equatorial locations provide an accurate data set of water vapor and ozone with high vertical resolution around the tropical tropopause. Observations are analyzed here for San Cristóbal, Galápagos, Ecuador, in the eastern Pacific; Juazeiro do Norte in northeastern Brazil; along a ship cruise in the western equatorial Pacific; and Christmas Island in the central equatorial Pacific. At San Cristóbal, observations began in 1998 on a campaign basis and are ongoing as part of Soundings of Ozone and Water in the Equatorial Region (SOWER) [*Hasebe et al.,* 1999], with the most recent campaign in November-December 2001. The observations are limited to ozone and water vapor. There is no direct evidence for the presence of ice particles; however, supersaturation observed in most spring profiles combined with large temperature variations during the observation period strongly suggest the presence of ice particles. High relative humidities well above ice saturation can force ice particle formation through homogeneous nucleation, and the subsequent sedimentation of these particles would lead to the removal of water substance. Thus, the observations of supersaturation with respect to ice imply dehydration, allowing a study of some of the characteristic processes at the tropical tropopause and of the regions that control the amount of water vapor entering the stratosphere. These processes are shown as a schematic in Figure 4.25.

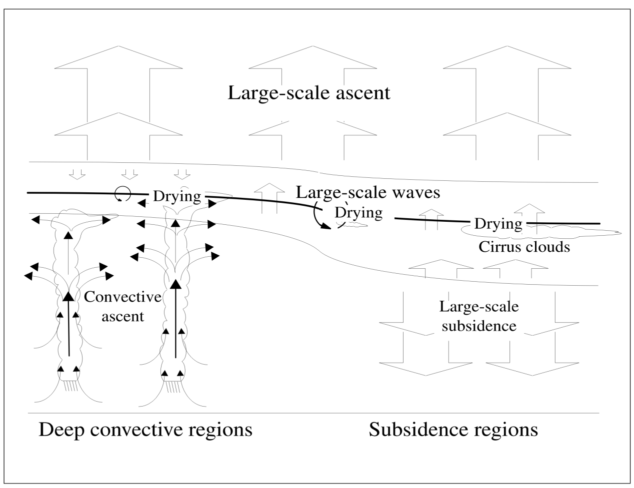

Fig. 4.25. Schematic of the transport and dehydration processes across the tropical tropopause. The tropopause is indicated by the solid thick line; the tropopause transition region is indicated by thin lines above and below. Drying occurs at the temperature minimum close to the lapse-rate tropopause, induced by convection, large-scale waves, and slow ascent. Breaking of large-scale waves is one of the sources of ozone in the tropopause transition region below the tropopause. The impact of the different deep convective regions on the transition region depends on the altitude reached by typical convection within each region.

Deep convection in the western Pacific transports lower tropospheric air to the tropopause, dehydrating the air to very low mixing ratios, while maintaining high relative humidities and low ozone concentrations [*Vömel et al.*, 1995]. Downward motion in the lower stratosphere above regions of deep convection [*Gage et al.,* 1991; *Sherwood*, 2000] may be responsible for the extremely steep gradients of water vapor and ozone observed directly at the tropopause. Away from regions of deep convection, subsidence lowers the relative humidity in the middle troposphere; however, the upper troposphere remains at high relative humidities and low ozone values indicative of the recent convective origin of the air. In regions where deep convection does not reach the tropical tropopause or where subsidence prevails, saturation and subsequent dehydration within the transition layer may still occur, driven only by slow, large-scale ascent [*Vömel et al*., 2002]. Kelvin waves and other large-scale waves may contribute to the dehydration process in these regions [*Fujiwara et al*., 2001]. Not all equatorial regions show saturation, and some regions may not participate at all in the dehydration of rising air. There is a strong seasonal cycle in the dehydration process at the tropical tropopause. At San Cristóbal, nonconvective dehydration was observed during the March campaigns, but not during the September campaigns.

A transition region around the tropopause can be identified by the increase in relative humidity with altitude up to the tropopause [*Vömel et al*., 2002], in addition to the increase in ozone [*Folkins et al*., 1999]. While wave breaking across the tropical tropopause and midlatitude intrusions are sources for ozone in this transition region [*Fujiwara et al*., 1998], the general upward motion in the transition region driven by the stratospheric extratropical pump [*Holton et al*., 1995, and references therein] maintains a high relative humidity within this layer. The seasonal cycle of relative humidity within the transition region is driven by the seasonal cycle of the stratospheric extratropical pump. In addition, the relative importance of different regions for the dehydration process changes with season. Based on CMDL measurements from several equatorial sites, it appears that the zonal average of the tropopause relative humidity shows a seasonal cycle as well. Furthermore, the seasonal cycle of the tropopause temperature shows a rapid cooling between September and December. The water vapor mixing ratio of 6 ppmv, when air passed the tropical tropopause in September, is not found later at higher altitudes when the new seasonal minimum at the tropopause is established (Figure 4.26), indicating a secondary or continuing dehydration of this air through December [*Vömel et al*., 2002]. Since average vertical velocities in the lower stratosphere are significantly larger during the northern winter, it appears that the northern winter months play a stronger role than the northern summer months in the dehydration of air entering the stratosphere.

Considering that the tropopause temperature in the equatorial eastern Pacific during September is too warm to allow saturation and the presence of cirrus clouds, reports of subvisible cirrus in this region may indicate that these clouds are not ice clouds but rather a mixture of nitric acid

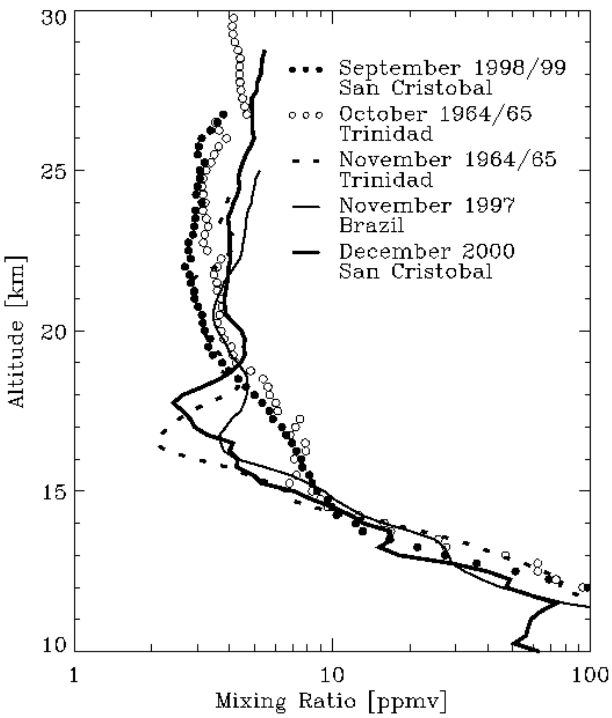

Fig. 4.26. Development of the dehydration between September and December. The profiles at San Cristóbal and Trinidad are the average for all profiles of the month(s); the profile at Juazeiro, Brazil, is a single profile.

and water similar to some types of stratospheric clouds found in the winter polar stratosphere.

CMDL's analysis identified three different dehydration processes that can occur at the tropical tropopause. It also showed that not all regions participate in dehydration of air in the tropopause transition region. Air entering the stratosphere will most likely have experienced a mixed history of the various dehydration and mixing processes, making quantitative modeling very difficult. There is a regional preference as well as a seasonal preference for dehydration, and the transport of water vapor into the stratosphere does not occur in a temporally and spatially uniform manner. This is contrary to the analysis by *Dessler* [1998], who suggested that theories including spatial and temporal preference “are no longer necessary.” *Newell and Gould-Stewart* [1981] suggested that air enters the stratosphere predominantly over the western Pacific during the northern hemisphere winter and early spring, as well as over the Indian Ocean during the monsoon season; they called this phenomenon the "stratospheric fountain." However, the sharp gradients of water vapor and ozone at the tropopause in deep convective regions, as well as the offset between regions of deep convection and regions of coldest tropopause temperatures [*Nishida et al.*, 2000], indicate that the regions of deep convection are not necessarily where air enters the stratosphere. The regional and seasonal preference for the dehydration process still needs to be quantified in detail.

Deep convective regions play an important role as a source of air in the transition region below the tropopause. This air may be transported horizontally away from the area of deep convection before entering the stratosphere [*Holton and Gettleman*, 2001]. Furthermore, overshooting deep convection may directly inject air into the lowermost stratosphere. If the tropopause temperature is cold enough, air in the transition region may be dehydrated further in nonconvective regions. The extratropical stratospheric pump provides a zonally averaged view, but there is no reason to assume that the vertical ascent in the lower tropical stratosphere is zonally symmetric. CMDL's analysis has not addressed this issue, but studies showing descending motion above the deep convective regions in the maritime continent already indicate that there are important zonal asymmetries in the vertical ascent in the lower tropical stratosphere. It is plausible that cold tropopause temperatures also correlate with regions of stronger vertical ascent, which would not only imply a regional preference for the dehydration of air entering the stratosphere, but also a regional preference for the entry point. It is also important to point out that there has been a significant increase in stratospheric water vapor [*Oltmans et al.*, 2000] and, at the same time, a decrease in the tropical tropopause temperature [*Zhou et al.*, 2001]. These two trends are not easily reconcilable. They also show that the atmosphere that led to the formulation of the stratospheric fountain hypothesis has changed and that the conclusions that are derived now will necessarily be different without refuting the stratospheric fountain hypothesis.

As a last point, the classifications "stratospheric" and "tropospheric" for air that is respectively above and below the lapse-rate tropopause need to be questioned. Air in the transition region has stratospheric signatures, like higher ozone concentrations and higher vertical stability than air in the middle troposphere. At the same time, this air has higher values of relative humidity and typical tropospheric tracers as well as the potential for cloud formation. In this region there is a mixture of both stratospheric and tropospheric air, and the question of whether convection overshoots the tropopause or not should be replaced by questions of how deep convection penetrates into the transition layer and how much nonconvective and wave-driven processes contribute to the makeup of the air in this region.