4.2.2. Water Vapor and Ozone Observations at San Cristóbal, Galapagos

In March 1998 profile measurements of ozone and water vapor were started at San Cristóbal. This project is conducted in cooperation with the University of Ibaraki, Japan, the University of Hokkaido, Japan, and the SHADOZ project. Water vapor profiles were measured in four campaigns during the spring and fall seasons of 1998 and 1999 and are scheduled to continue in the fall of 2000. The main instrument is a balloonborne frost-point hygrometer, and in three cases a new commercial frost-point hygrometer was tested that could extend the altitude range of upper tropospheric humidity measurements for smaller radiosonde-type soundings. Regular ozone soundings have been launched biweekly since September 1998 and weekly since March 1999. The excellent location and the outstanding data quality received from this site will hopefully allow continued soundings. Despite the political and economic problems of Ecuador, which continue to impact the operation of this project, it was undertaken successfully.

San Cristóbal is strongly influenced by El Niño/La Niña events and is, therefore, a natural laboratory for atmospheric processes controlled by the upwelling and the downwelling part of the Walker circulation. It is one of the few tropical regions that has significant periods of clear sky and is highly suitable for remote sensing studies and radiometry as well. It is currently the only tropical site where water vapor near the tropopause is measured and is the only site adding to the database for water vapor entering the stratosphere through the tropical tropopause. Its remoteness from industrial pollution sources allows for the study of long-range transport of pollutants across the tropical Pacific region.

Water Vapor Crossing the Tropical Tropopause

Since the discovery of the stratospheric dryness [*Brewer*, 1949], it is generally accepted that air enters the stratosphere predominantly in the tropics because only the tropical tropopause is cold enough to explain the low water vapor content of the stratosphere. Early investigations based on radiosonde and in situ measurements [*Newell and Gould-Stewart*, 1981; *Kley et al.*, 1982] indicated that there is a regional and temporal preference for air entering the stratosphere. A strong focus of the early investigations has been deep convective systems and their cirrus anvils [*Danielsen*, 1982, 1993]. These systems can achieve water vapor mixing ratios at the tropopause well below the mean stratospheric water vapor concentration [*Vömel et al.*, 1995]. *Yulaeva et al.* [1994] have shown that the mean tropical tropopause temperature is mostly controlled by the seasonal cycle of the mean residual vertical velocity in the stratosphere, which implies that tropical tropopause regions not influenced by tropical deep convection might still become sufficiently cold to dry slow rising air. Several studies [*Dessler*, 1998; *Sherwood*, 2000; *Gettelman et al.*, 2000] indicate that a regional preference for air crossing the tropical tropopause may not be necessary to explain the stratospheric dryness.

Our first campaign took place in March 1998 at the end of the very strong El Niño event of 1997/1998. During this campaign the average minimum temperature near the tropopause was around -83ºC with a saturation mixing ratio of about 3.6 ppmv (Figure 4.8a). While the atmosphere was convectively more active during this campaign because of the El Niño event, there is no indication that the deep convection reached the local tropopause. Therefore, the tropopause temperature did not appear to be directly controlled by the deep convection. This is in strong contrast to our results from the Central Equatorial Pacific Experiment (CEPEX) in 1993, where deep convection reached the tropopause and directly caused extremely low tropopause temperatures and water vapor mixing ratios.

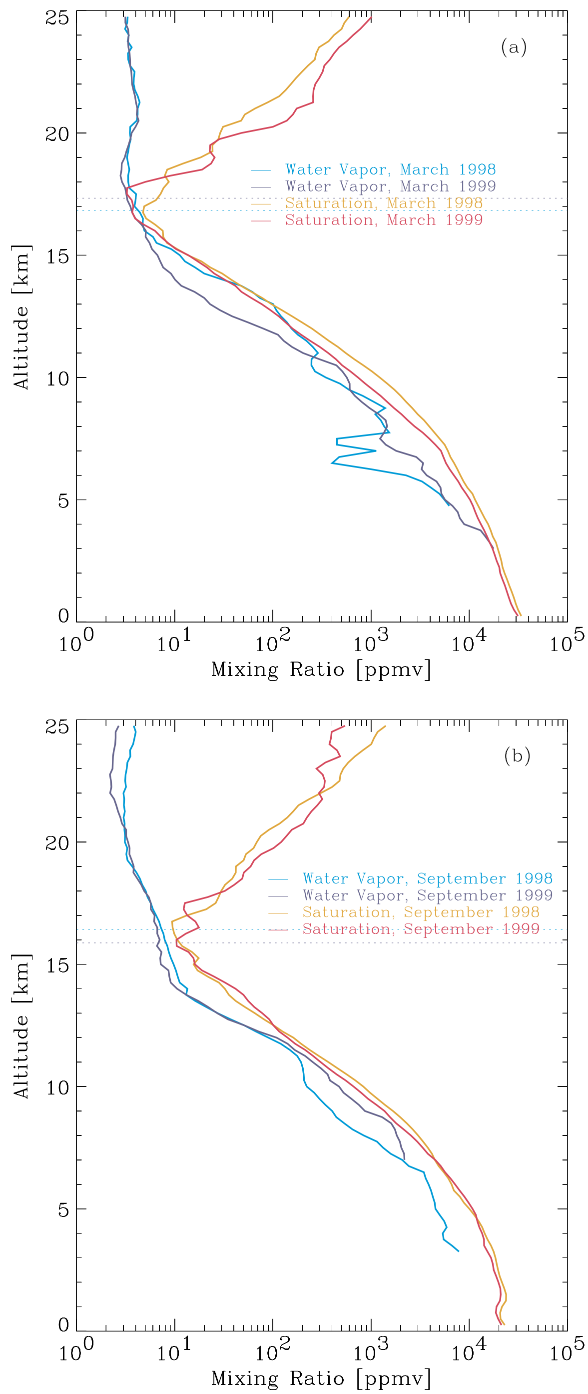

Fig. 4.8. San Cristóbal, Galapagos, average water vapor (blue) and saturation (red) mixing ratios for (a) March 1998 and March 1999, (b) September 1998 and September 1999. The dotted line shows the height of the tropopause in 1998 (light blue) and 1999 (dark blue).

Nevertheless, the first frost-point sounding at San Cristóbal showed a saturated layer between 13 km and the tropopause at 17 km above a very dry layer between 6 and 12 km with humidity values between 10 and 20%. The later soundings of this campaign showed a warmer tropopause and only up to 90% saturation of water vapor over ice with a more moist middle troposphere. These soundings indicate local drying at the tropopause may occur but is not necessarily related to deep convection. The campaign in March 1999 confirmed this result clearly without the influence of deep convection. The soundings typically showed a dry layer between 11 km and 16 km and a considerable increase in ozone above 11 km. This indicates downward transport in the upper troposphere corresponding to the descending part of the Walker circulation.

In both fall campaigns (Figure 4.8b) the tropopause was significantly warmer, around –78ºC, with a saturation mixing ratio between 5 and 12 ppmv. The water vapor soundings showed a dry layer below and up to the tropopause except for the actual temperature minimum, which in some cases could reach up to 90% relative humidity (ice). The measured water vapor mixing ratio at the temperature minimum of the tropopause ranged between 5.5 and 7.5 ppmv. Local drying at the tropopause level was not observed; however, relatively higher water vapor mixing ratios at the tropopause indicate air may enter the tropical lower stratosphere without being dried locally at the temperature minimum.

CMDL observations at San Cristóbal indicate there is a region below the local tropopause that is not directly influenced by deep convection. This region constitutes a barrier to vertical mixing below the local tropopause. This result has been found for other tropical sites [*Folkins et al.*, 1999] and is indicated here in terms of ozone and water vapor.

The results during CEPEX in the western Pacific showed that deep convection can reach the local tropopause causing extremely low temperatures and drying air to extremely low water vapor mixing ratios. In contrast to these observations, our results at San Cristóbal indicate that in the eastern Pacific region deep convection does not reach as high, and that cold tropopause temperatures are achieved by stratospheric processes rather than by tropospheric deep convection. Local drying does occur during the northern spring seasons, but not during the northern fall seasons. Furthermore, air that is unsaturated at the local temperature minimum near the tropopause may enter the tropical lower stratosphere during these months.

Tropospheric Ozone Observations

Extremely low ozone values observed in the middle and upper troposphere in the western Pacific [*Vömel et al.*, 1995] have not been observed in the eastern Pacific (Figure 4.9). This indicates that deep convection, which can transport ozone-poor air rapidly from the boundary layer to the upper troposphere, is not as vigorous in the eastern Pacific as it can be in the western Pacific. However, there is a significant difference in the upper tropospheric ozone observed during the March 1998 campaign compared to the March 1999 campaign (Figure 4.9a). The first campaign in March 1998 was still under the influence of the El Niño of 1997/1998 that moved the typical upwelling region of the Walker circulation towards the central and eastern Pacific. The upper tropospheric ozone during this campaign shows lower values compared to the campaign of the following year, indicating that the El Niño event caused increased transport of boundary layer ozone into the upper troposphere. In the fall campaigns (Figure 4.9b) ozone concentrations in the upper troposphere are significantly higher than for March 1999. In both years the average ozone profiles during the fall campaigns do not show the difference that was seen in the two March profiles, possibly because both campaigns were under similar La Niña conditions.

San Cristóbal is considered a remote marine site, far from industrial sources of pollution. However, it is often influenced by long-range transport from biomass burning regions and other pollution sources of South America. Figure 4.10 shows a time/height cross section of the ozone mixing ratio for 1999 over San Cristóbal. The middle troposphere shows a seasonal cycle with higher ozone values typically found between August and October and lower values between January and May. Trajectory analyses show that during most time periods the air comes predominantly from equatorial South America. During June through August, for example, more than 90% of all trajectories arriving at 6 km over San Cristóbal originate over equatorial South America, in particular from the biomass burning regions of the Amazon basin and northeastern Brazil.

The sounding on May 18, 2000, shows some direct evidence for long-range transport from the South American continent (Figure 4.11). At 5 km altitude this sounding displays a shallow layer apparently devoid of ozone. While ozone is most likely undisturbed within this layer, its signal is masked by an artifact of the instrument caused by high concentrations of SO_2. The likely source for this layer is an eruption plume of Tungurahua volcano (78.44ºW, 1.74ºS) on May 13 transported to Galapagos within 5 days.

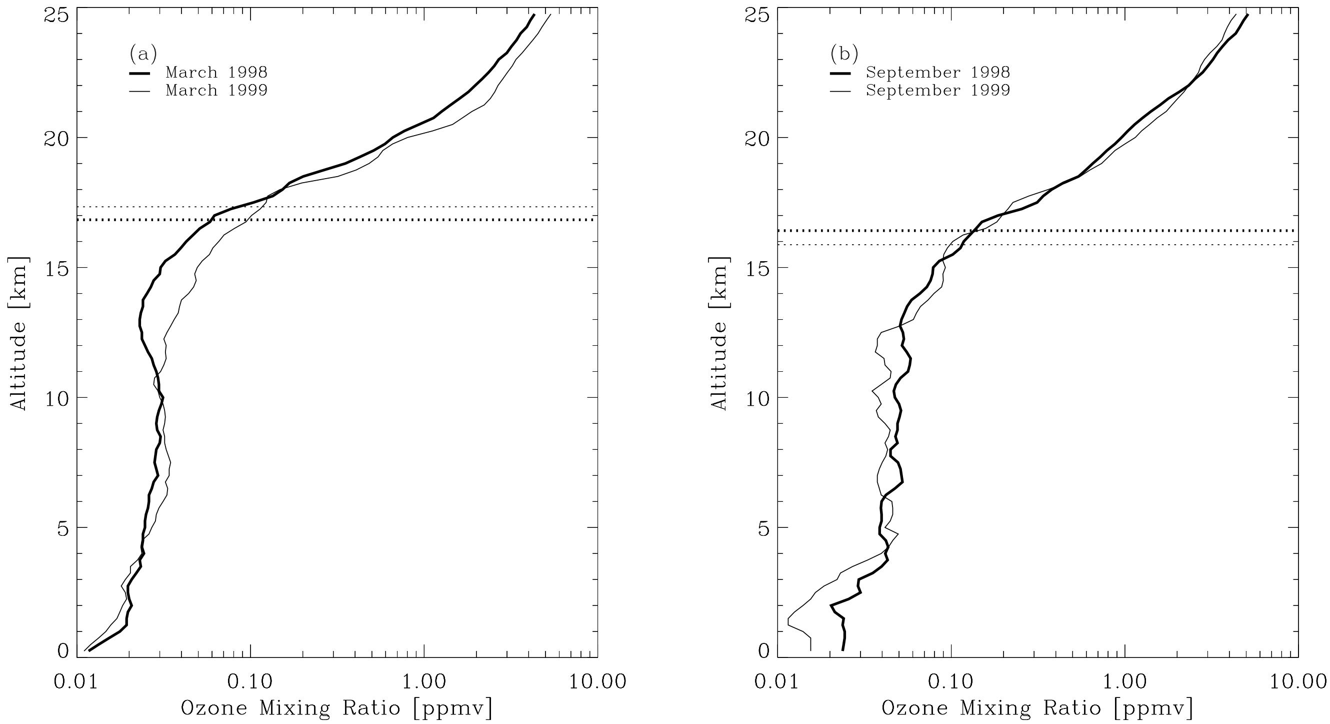

Fig. 4.9. San Cristóbal, Galapagos, average ozone mixing ratios for (a) March 1998 and March 1999, (b) September 1998 and September 1999. The height of the tropopause is shown for 1998 (dark dashed line) and 1999 (light dashed line).

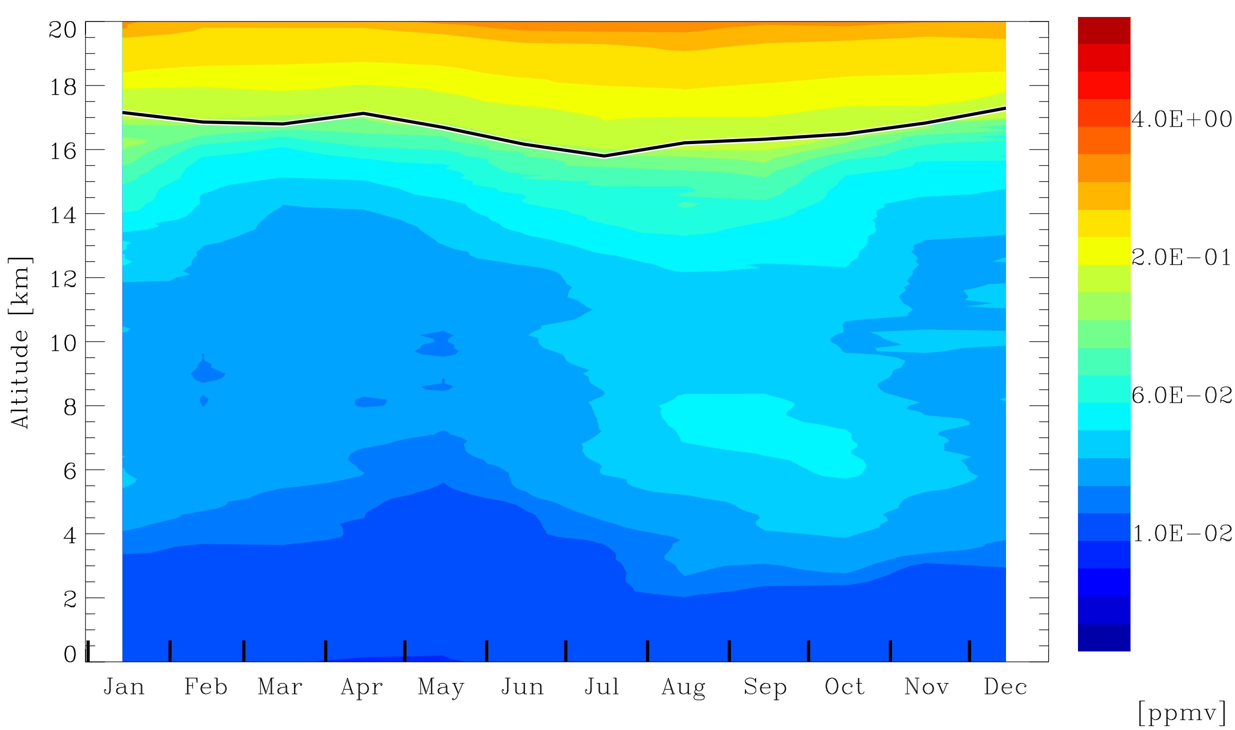

Fig. 4.10. Time/height climatology of monthly averages of ozone mixing ratio over San Cristóbal, Galapagos, in 1999. The solid line indicates the average tropopause height.

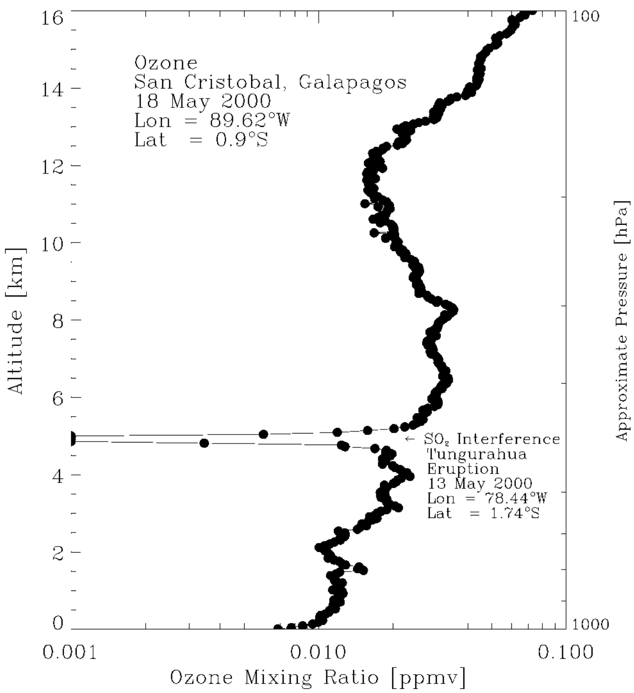

Fig. 4.11. SO_2 interference layer caused by long range transport of volcanic gases emitted by Tungurahua volcano May 13, 2000, and observed May 18, 2000, at San Cristóbal, Galapagos.

Outlook

The location of this site is very unique and continued observations are planned in the near future. These observations will be included in satellite validation studies. A new surface ozone monitor at this site will give 24-hr observations of boundary layer concentrations of ozone that will allow for the study of some interesting aspects of the chemistry of the lower troposphere.