Journal of the Meteorological Society of Japan, Vol. 80, No. 4B, pp. 897–909, 2002

Ozonesonde Observations in the Equatorial Eastern Pacific —the Shoyo-Maru Survey—

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(Manuscript received 5 September 2001, in revised form 13 March 2002)

Abstract

We have conducted GPS radiosonde and ozonesonde observations on board the research vessel “Shoyo-Maru” in the equatorial eastern Pacific. These observations took place in September and October 1999 as a part of the Soundings of Ozone and Water in the Equatorial Region (SOWER)/Pacific mission. The mean profile of ozone is similar to that for the dry season (September to October) at San Cristóbal, Galápagos (0.9°S, 89.6°W) located in the equatorial eastern Pacific. The mean tropospheric ozone concentration is about 40 ppbv with a maximum in the mid-troposphere. Compared with the mean profile during the dry season at Watukosek, Indonesia (7.5°S, 112.6°E), this mid-tropospheric maximum is larger, and a sharp increase of ozone below the tropopause begins at a lower altitude for the Shoyo-Maru

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profile. We frequently observed layers in which ozone and humidity are highly anti-correlated. These layers have vertical scales from several kilometers to several hundred meters. Horizontal scales of these layers are roughly 1000 km, which may correspond to time scales of about 2 days, since the vessel sailed about 500 km/day. These layers are related to northerly winds, which bring in wet and ozone-poor air from the inter-tropical convergence zone situated in the northern side of the main cruise track. Similar layers were observed in ozone profiles at San Cristóbal and Watukosek, mostly during the dry season, suggesting the existence of layers advected without vertical mixing.

1. Introduction

Equatorial total ozone variations are dominated by annual, quasi-biennial, and El Niño-Southern Oscillation (ENSO) time scales (Shiotani 1992). Using vertical ozone profiles from the Stratospheric Aerosol and Gas Experiment II (SAGE II), Shiotani and Hasebe (1994) identified the height range over which each of the total ozone variations dominate. They found above the tropopause level that the annual and ENSO-related variations are constrained to the lower-most stratosphere, while the quasi-biennial oscillation (QBO) in ozone is mostly seen above 20 km, in the lower and mid-stratosphere. They also found that the zonal wavenumber 1 pattern, observed in total ozone over the equatorial latitude, could be attributed to the longitudinal variation of tropospheric ozone, which originally had been proposed by Fishman and Larsen (1987).

In view of the lack of important ozone observations at low latitudes, we started ozone and water vapor sonde observations in the equatorial Pacific. Since 1998 the Soundings of Ozone and Water in the Equatorial Region (SOWER)/Pacific mission (Hasebe et al. 2001) has been conducted on a campaign basis at San Cristóbal, Galápagos, Ecuador (0.9°S, 89.6°W) and Christmas Island, Kiribati (2.0°N, 157.5°W) supplementing the on-going program at Watukosek, Indonesia (7.5°S, 112.6°E). Results from these campaigns have been contributing to the understanding of stratosphere-troposphere exchange (e.g., Fujiwara et al. 2001; Vömel et al. 2002) and to the equatorial tropospheric ozone distribution which will be described in this paper.

In September/October 1999, we had the opportunity to join a cruise of the "Shoyo-Maru", a research vessel of the Fisheries Agency of Japan, investigating the fishery resources in the central and eastern tropical Pacific. The scientific target of this cruise covers both dynamics and chemistry of oceans and atmosphere. In addition to the regular radiosonde observations, we conducted the first ship-borne ozonesonde observations in the equatorial eastern Pacific.

In recent years the SHADOZ (Southern Hemisphere ADditional OZonesondes) project has been filling the gap in equatorial ozonesonde observations (Thompson et al. 2002; Fujiwara et al. 2000). Earlier shipboard observations of the vertical distribution of ozone were mostly conducted crossing the Atlantic (Herman et al. 1989; Weller et al. 1996; Thompson et al. 2000). One equatorial mission in the western and central equatorial Pacific was reported by Kley et al. (1997). Ozonesonde observations in the Indian Ocean have been conducted recently (Zachariasse et al. 2001). However, there have been no shipboard ozonesonde observation in the equatorial eastern Pacific. The only site, where ozonesonde data exist in the eastern equatorial Pacific is San Cristóbal, Galápagos.

This paper will present the first study of the vertical ozone distribution in the equatorial troposphere and stratosphere and its relation to the meteorological background field over the eastern Pacific on the basis of the Shoyo-Maru cruise during September/October 1999. General information about the ozonesonde soundings are described in section 2. Results are presented in section 3, first about the mean state, focusing on the troposphere, then about layers in the ozone and humidity profiles; GPS radiosonde data are used to confirm typical spatial or time scales of these layers. Finally we use the San Cristóbal and Watukosek ozonesonde data to investigate the seasonality of these layers. A summary is in section 4.

2. Ozonesonde soundings

GPS radiosondes were launched four times a day, while ozonesondes were launched once a day. A Vaisala ozonesonde system (Science Pump ECC ozonesonde connected to a Vaisala GPS radiosonde) was launched on a TA1200 Totex balloon to measure the vertical distribution of ozone and meteorological parameters. The balloons were prepared in a U-shaped wind screen made of strong vinyl in the back of the observation deck of the Shoyo-Maru. Near the equator headwinds of about 15 ms^{-1} were encountered, while the ship was moving eastward with a speed of about 6 ms^{-1}. The wind screen, however, provided almost complete protection. The amount of Helium gas needed to fill the balloons was measured using the pressure gauge attached to the gas cylinders. Before the launch of an ozonesonde, we slowed the ship to a relative wind speed of about 10 ms^{-1}. No slow down was necessary to launch GPS radiosondes.

The ozone measurements have an accuracy of 5–10% in the troposphere and $\sim$5% in the lower stratosphere. The influence of the ship's exhaust on the ozone measurements was confined to the lowest few hundred meters at most. The response time of the ECC ozone sensor can be as low as 20 sec (Komhyr and Harris 1971), but in practice the sensor indicates an 80–90% response to step changes in ozone in about 50–60 sec, depending somewhat on the solution volume and temperature (Komhyr et al. 1995). This corresponds to a vertical distance of 250–300 m, assuming a typical ascent velocity of about 5 ms^{-1}. The response time is sufficient to detect the layered structures, which will be discussed in sections 3.3 and 3.5, but there may be some small phase shift between the profiles of ozone and other parameters.

Regular meteorological soundings were conducted using a Vaisala GPS radiosonde (RS80-15G). The humidity sensor is a Humicap-A type thin-film capacitor, which can measure relative humidity (RH) up to 11 km in the tropics (World Meteorological Organization 2000; Miloshevich et al. 2001). Here, we follow the convention to report RH with respect to liquid water. RH profiles are plotted up to 11 km, however, a longitude-height cross-section of RH is drawn up to 16 km to show the variability in the upper troposphere, even though errors and systematic biases in the upper troposphere become very large.

Figure 1 shows the cruise track and the locations of the sonde releases together with the ceiling altitude of these soundings. A total of 14 successful ozonesondes was launched from September 19 to October 3, in addition to 49 regular radiosondes from September 18 to October 7. Ozone soundings 3 through 9 were launched on the 2°N parallel. Climatologically the intertropical convergence zone (ITCZ) in the eastern Pacific is close to 4° $\sim$ 8°N (e.g., Philander 1990). From September 17 to September 21, the ship sailed southeast from Hawaii to 2°N, 140°W, crossing the wet region at around 8°N (see Fig. 7). From October 1 to 7, the ship sailed close to the ITCZ north of the Galápagos Islands. Along the 2°N parallel, the weather was fine and no rain was encountered. Because the vessel was moving mostly eastward with an average speed of about 6 ms^{-1}, some of the longitude-height cross-sections shown in this paper may also be interpreted as time-height cross-sections. In other words a characteristic horizontal scale of a feature may be translated into a characteristic time scale.

At the same time, other SOWER team members performed campaign observations at the SOWER bases, San Cristóbal and Christmas Island (see Fig. 1). Unfortunately the ozonesonde observations at Christmas Island were limited due to the receiver problems. These results will not be presented here. At San Cristóbal, weekly ozonesonde observations were conducted by NOAA/CMDL as a part of SHADOZ, in addition to the campaign observations. Here, we use the San Cristóbal data from March 1998 to December 2000. At Watukosek, we use the ozonesonde data from May 1993 to July 1999 for comparison. A part of these soundings has been contributed to the SHADOZ data archive. Because the ozonesonde data at Watukosek are highly affected by the 1997–1998 El Niño event, we exclude the data from April 1997 to March 1998 for the analyses presented here. All profile data for ozone and meteorological parameters are standardized to 50 m intervals, except for Watukosek, where data are standardized to 200 m intervals, due to the different sampling intervals for the system used there.

3. Results

3.1 Mean profiles

Figure 2 shows the mean profiles of temperature, RH, ozone, and horizontal wind compo-

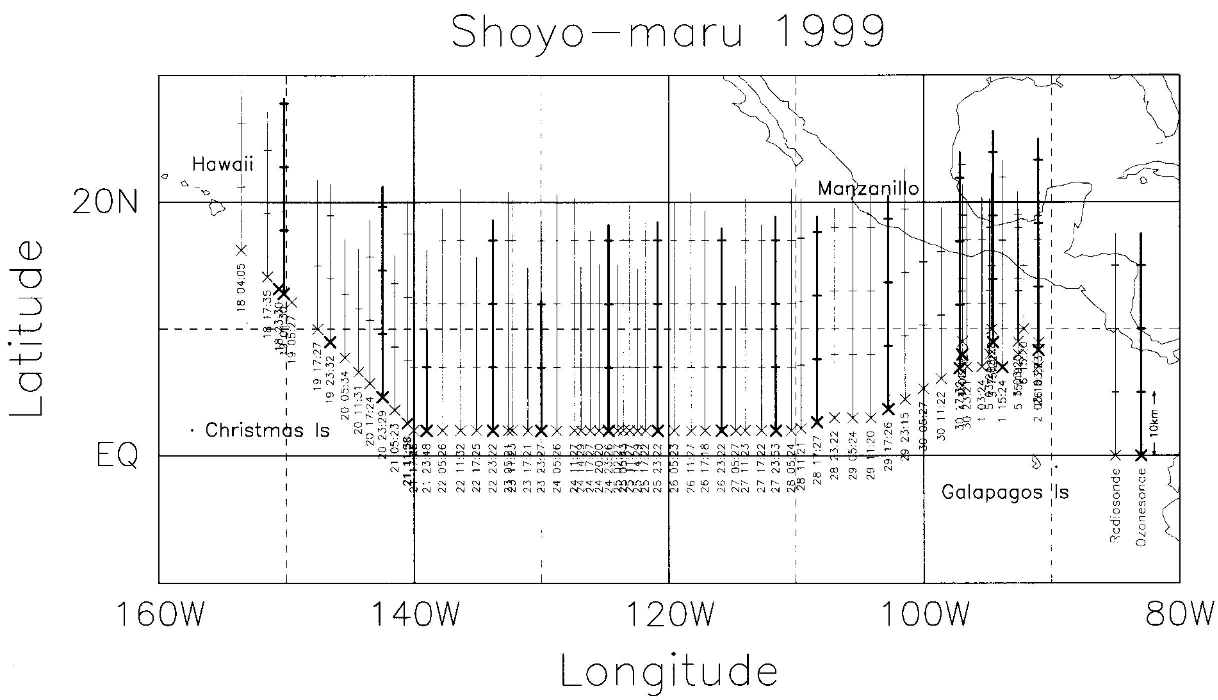

Fig. 1. Observation points of GPS radiosondes and ozonesondes with the ceiling altitude indicated by thin bars (radiosonde) and thick bars (ozonesonde). The balloon launch time (day of the month and UT) is shown as "dd hh:mm" (dd: day, hh: hour, mm: minute).

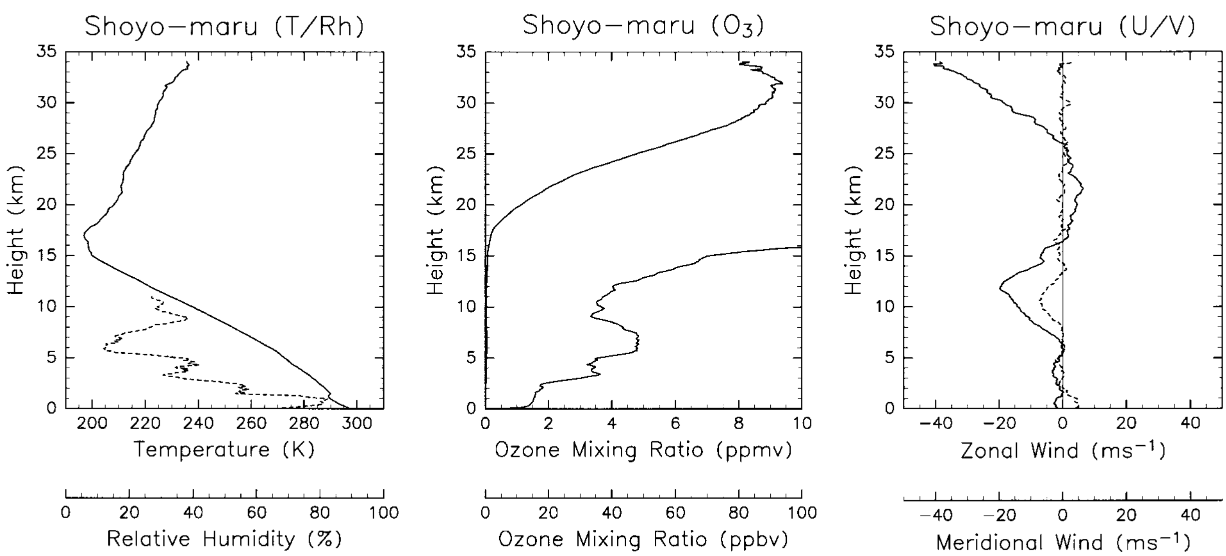

Fig. 2. Mean profiles averaged over all ozonesonde soundings. Left: temperature (solid line) and relative humidity (dashed line); center: ozone, with two scales, for the tropospheric and the stratospheric part; right: horizontal wind components. The zonal (solid line) and meridional (dashed line) wind.

nents averaged over all ozonesonde soundings, including those from the wet region associated with the ITCZ. The cold point tropopause is located around 17 km, and the marine boundary layer inversion is observed just above 1 km. The RH profile shows a minimum around 6 km and several steps below with a typical vertical scale of 1–2 km. This structure is persistent along 2°N (see Fig. 7 in Section 3.4).

The maximum ozone mixing ratio is around 9 ppmv at 31.9 km. In the troposphere the mean ozone profile shows a structure anticorrelated to the mean RH profile. Low values of RH correspond to high ozone concentration and vice versa. This large-scale layered structure will be discussed in detail in sections 3.3 and 3.5. A sharp increase in ozone below the tropopause starts around 12 km, which will be compared to the other equatorial stations in section 3.2.

The mean wind in the stratosphere is weak westerly between 16 and 26 km and the strong easterly above 26 km, which mostly reflects the quasi-biennial oscillation (QBO). Below the tropopause winds are mostly northeasterly, which may be attributed in part to the Mexican monsoon (e.g., Barlow et al. 1998). The meridional wind in the lowest troposphere is southerly, suggesting inflow to the ITCZ, which was located about 5° or 500 km north of the cruise track at 2°N. The easterly component in the lower troposphere represents the trade winds.

Gravity waves and other interesting variations can be identified in the stratosphere (Fig. 9), but here we concentrate on the tropospheric part of the observations.

3.2 *Tropospheric ozone*

Figure 3 shows a longitude-height cross-section of ozone. All profiles are separated by about 5° or about 500 km (Fig. 1). Average ozone concentrations in the troposphere are about 40 ppbv, with large variations in the vertical (Fig. 2). A relative minimum is generally located around 10 km, and a maximum around 7–8 km. In some cases other maxima can be found around 2 km and 4–5 km. We will discuss this layered structure in sections 3.3 and 3.4.

Figure 4 compares the mean profiles of ozone and temperature with those at San Cristóbal and Watukosek. The mean profiles for the

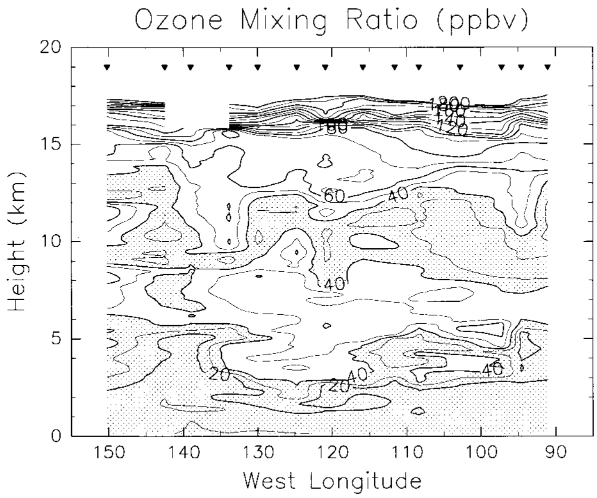

Fig. 3. Longitude-height cross-section of ozone (unit: ppbv). Ozonesonde data from September 18 through October 2 (marked on the top of the figure) are used, while the ship sailed eastward. Regions with less than 200 ppbv are contoured using an interval of 10 ppbv; values less that 40 ppbv are shaded.

Shoyo-Maru period (Fig. 4 (left)) are the same as Fig. 2, but limited to below 20 km. For San Cristóbal (Fig. 4 (center)) and Watukosek (Fig. 4 (right)) profiles for the dry season and wet season respectively are shown in thick and thin lines. At San Cristóbal we selected data from September to October to represent the dry season and from March to April to represent the wet season. At Watukosek the dry season is defined as August to October, and the wet season as December to March. The actual dry and wet seasons are longer than two months at San Cristóbal, but we use our not completely arbitrary definition since these months include our SOWER campaigns and the number of available data is relatively large. The profiles for Watukosek represent an updated Fig. 5 of Fujiwara et al. (2000). The seasonal cycle of tropospheric ozone at other equatorial SHADOZ stations including San Cristóbal is analyzed by Oltmans et al. (2001). Figure 4 indicates that the Shoyo-Maru profiles are very similar to the dry season profiles at San Cristóbal, but not to either dry or wet season profiles at Watukosek.

There is a large difference between the wet and dry season profiles at San Cristóbal. The

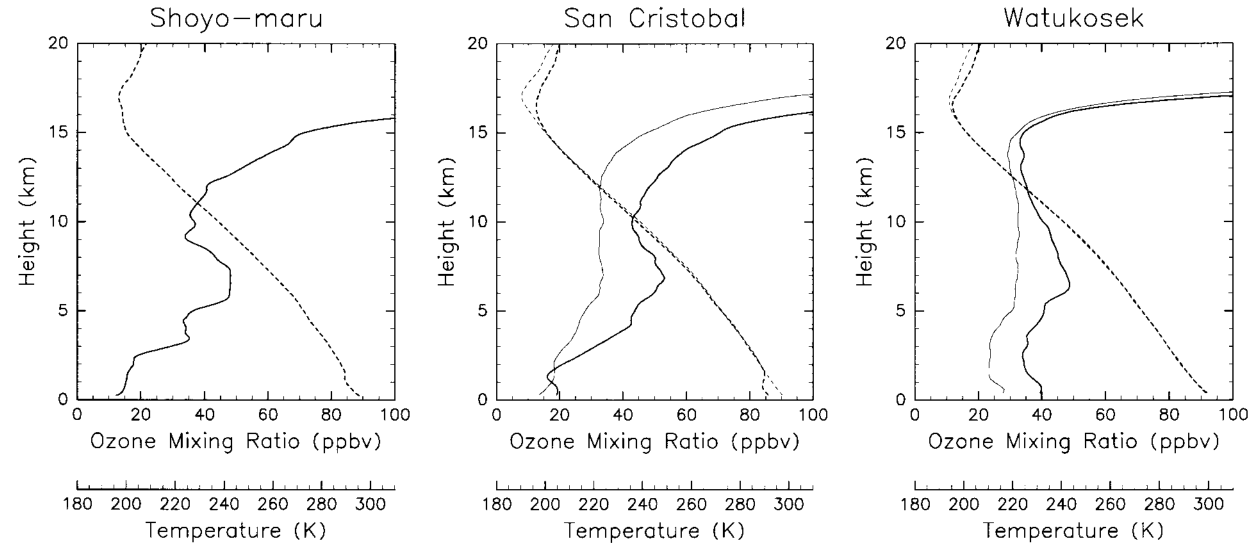

Fig. 4. Mean profiles of ozone (solid line) and temperature (dashed line) for the Shoyo-Maru period (left), San Cristóbal, Galápagos (center), and Watukosek, Indonesia (right). At San Cristóbal the dry season defines September through October, and the wet season March through April. For Watukosek the dry season defines August through October, and the wet season December through March. Profiles in the dry and wet seasons are plotted in thick and thin lines, respectively.

tropopause is higher during the wet season (northern winter and spring), in agreement with a typical annual cycle of tropical tropopause properties (e.g., Reid and Gage 1981; Randel et al. 2000; Hasebe and Koyata 2002). During the dry season, the sea surface temperature is significantly colder due to cold water upwelling off the west coast of South America, which causes a well developed marine boundary layer inversion. The ozone profiles also show marked differences between the wet and dry season. The mean value is larger during the dry season compared to the wet season with stronger enhancements in the mid-troposphere, which are most likely caused by long range transport of biomass burning outflow (Fujiwara et al. 1999, 2000; Oltmans et al. 2001). During the dry season, ozone amounts in the upper troposphere are larger, and the increase of ozone below the tropopause begins at a lower altitude compared to the wet season. However, the increase of ozone below the tropopause could also be influenced by the higher values in the mid-troposphere. During the wet season, the more active convection may lead to lower ozone concentrations in the troposphere and a vertically more uniform distribution, since convection can transport ozone poor air from the boundary layer up to the middle and upper troposphere.

The seasonal cycle at Watukosek is similar to that at San Cristóbal. The tropopause is lower in the dry season than in the wet season, though the difference between the two is smaller at Watukosek than at San Cristóbal. The mean value of ozone is slightly higher with similar enhancements in the mid-troposphere. However, the ozone profile in the upper troposphere is quite different. The altitude of the ozone increase below the tropopause is significantly higher and the difference between the two seasons is smaller at Watukosek than at San Cristóbal. This could be due to the different convective activity between the western and eastern Pacific. Using ozonesonde data at Samoa (14°S), Folkins et al. (1999) argued that a barrier to vertical mixing may exist at 14 km, which is now regarded as one of the indicators for the lower boundary of the tropical tropopause layer (TTL) (e.g., Highwood and Hoskins 1998). Our results suggest that the lower boundary of the TTL may depend on season as well as geographic location due to differences in convective activity. Ozone concentrations in

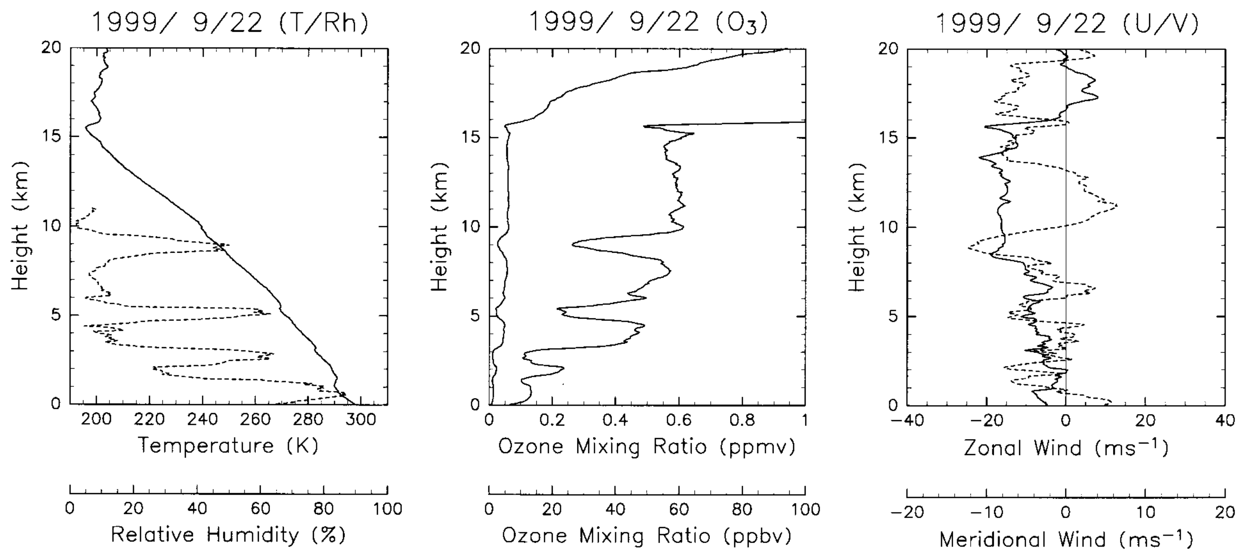

Fig. 5. Ozonesonde observation at 2.0°N and 133.8°W, September 22, 23:22 UT. The way of presentation for temperature, relative humidity, ozone and horizontal wind components is basically the same as Fig. 2 except that the height range is limited up to 20 km and that some scalings are different.

the boundary layer are always smaller at San Cristóbal compared to Watukosek, indicating that ozone destruction in the marine boundary layer may be more effective in the eastern Pacific.

The Shoyo-Maru mean ozone profile resembles the San Cristóbal mean profile during the dry season in the following points: Ozone is enhanced in the mid-troposphere; the increase of ozone below the tropopause is gradual; and ozone concentrations in the marine boundary layer are small compared to Watukosek.

3.3 *Ozone/RH layers—case studies*

During the cruise we frequently observed layered structures in ozone. Figure 5 shows an example, which was observed at 2.0°N, 133.8°W on September 22, 23:22 UT (the 4th observation from the west in Fig. 3). The ozone profile shows three distinct ozone-poor layers around 2.5–3 km, 5 km and 9 km. The vertical scale of the ozone poor part is typically around 1 km. These layers are almost perfectly anticorrelated to layers of high RH. The temperature profile shows correspondingly slight inversions. In the wind profile, northerlies dominated when ozone is low and RH is high. These correlations support the idea that northerly winds bring in wet and ozone-poor air from the ITCZ, roughly 5° to the north.

Figure 6 shows another example from 2.0°N, 111.6°W on September 27, 23:53 UT (the 8th observation from the west in Fig. 3). Again, ozone and RH show a strong anticorrelation, with several ozone rich and dry layers. The vertical scale of wet and dry layers is not as uniform compared to Fig. 5, but the correlation with the northerly winds is equally striking.

Layered structures like these have a long history back to Danielsen et al. (1987) and have been extensively investigated from airborne observations during PEM-West A in the western Pacific (Newell et al. 1996) and PEM-Tropics A in the central and eastern Pacific (Stoller et al. 1999). Their observations include CO and CH_4 in addition to O_3 and H_2O. They calculated correlations between the two of these four species to infer the origin of the air such as polluted air, stratospheric air, clean air and so on. It seems that our observations in the equatorial eastern Pacific are similar to the observations by Stoller et al. (1999) in the western Pacific, because the layers they found have a thickness of order 1 km and a horizontal ex-

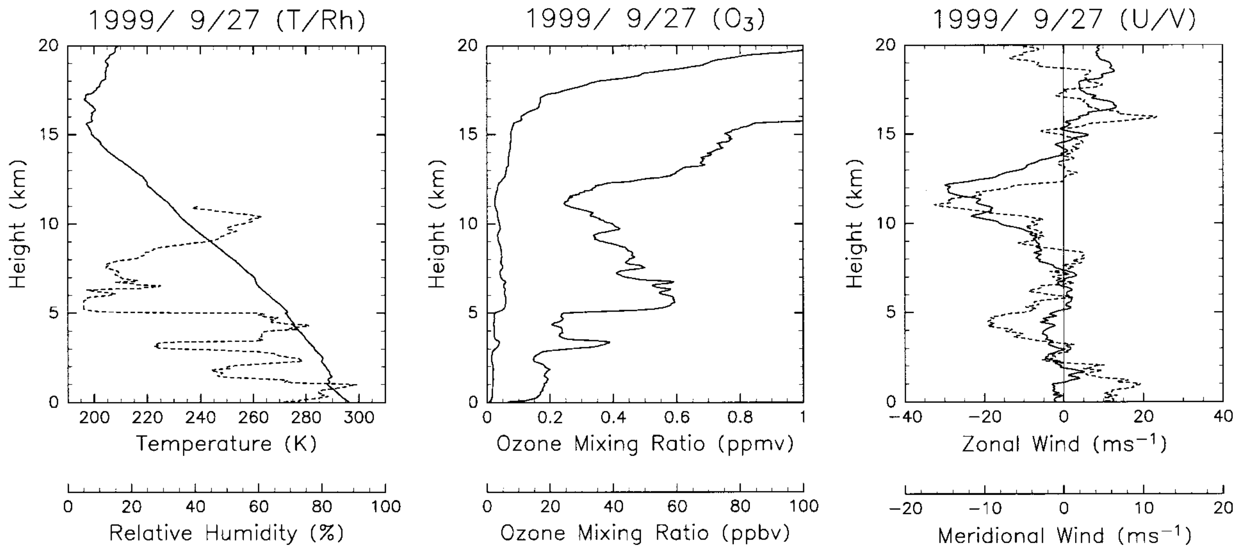

Fig. 6. Same as Fig. 5 for 2.0°N and 111.6°W, September 27, 23:53 UT.

tent of order 1000 km, though the origin is not as clear.

3.4 Radiosonde observations

To investigate the extent of these layers we use data from radiosoundings, which were launched 4 times daily. Figure 7 shows a longitude-height cross-section of RH observed by the radiosondes. This is a similar representation as Fig. 3, however, with a much denser spacing, including all radiosonde launches. The dry region between 5–8 km, shown already in the average profile of Fig. 2, is here resolved horizontally. The distinct wet region around 145°W corresponds to the soundings when the ship crossed the ITCZ at 8°N (see Fig. 1). Toward the eastern end the air in the mid- and lower troposphere becomes more moist as the ship sailed north-east towards the ITCZ. The examples of the layered structures in Figs. 5 and 6 are at 133.8°W and 111.6°W (the 4th and 8th ozonesonde observations from the west), respectively. The region around 10 km is quite different between these two cases. The low RH at 133.8°W has a relatively short lifetime or small horizontal extent with a distinct relative maximum in RH below at around 9 km. However, the higher humidity in the 10 km region at 111.6°W appears more persistent in time or in longitude, and gradually descended as the ship sailed eastward. At and below 5 km, the layers persist with a horizontal scale of about 10 degrees (~1000 km), which may correspond to a time scale of about 2 days, using a ship velocity of about 500 km/day. Stoller et al. (1999)

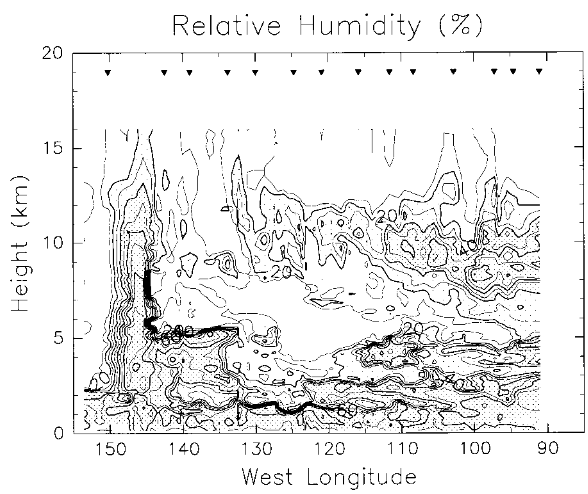

Fig. 7. Longitude-height cross-section of relative humidity (unit: %). GPS radiosonde data from September 18 through October 2 are used, while the ship sailed eastward. Data up to 16 km are contoured. Contour intervals are 10%, and values > 20% are shaded. Points of ozonesonde observations are marked on the top of the figure.

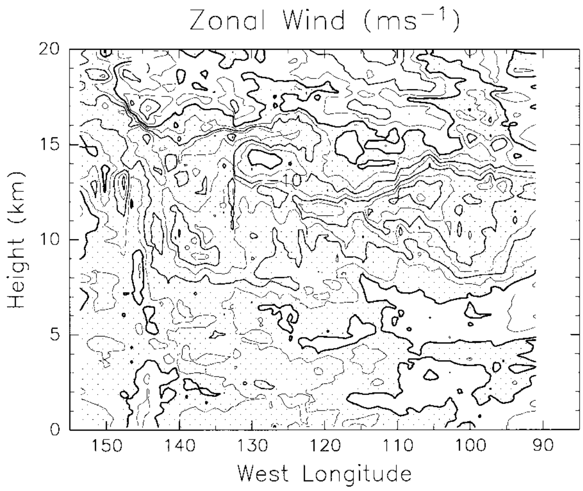

Fig. 8. Same as Fig. 7 for the zonal wind component (unit: ms^{-1}). Contour intervals are 5 ms^{-1}, easterlies are shaded.

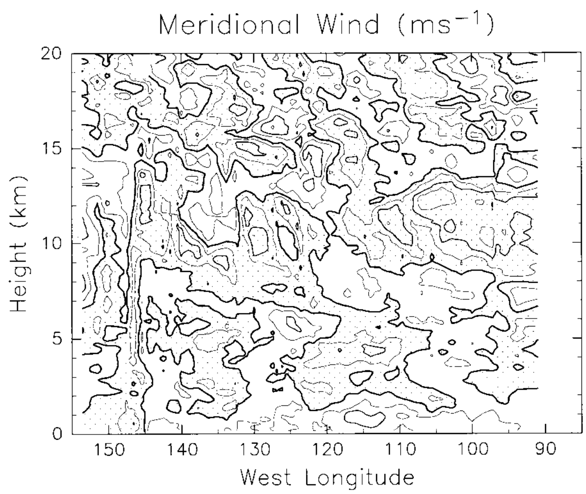

Fig. 9. Same as Fig. 8 for the meridional wind component (unit: ms^{-1}). Contour intervals are 5 ms^{-1}, northerlies are shaded.

estimated the horizontal extent of these layers to be on the order of 1000 km, similar to our estimate.

The zonal wind (Fig. 8) seems to have no clear relation to these layers. One noticeable feature is that there are strong (>30 ms^{-1}) easterlies in the upper troposphere in the eastern part of the cruise. In the same region, the meridional wind field (Fig. 9) shows relatively strong northerlies. These northeasterly winds in the upper troposphere may indicate an influence of the Mexican monsoon (e.g., Barlow et al. 1998).

Figures 7 and 9 show that regions of high RH region usually correspond to northerly winds. This correlation is mostly true in the lower troposphere and to some lesser extent in the mid-troposphere ($\leq$10 km). Above 14 km there are meridional wind variations, which at San Cristóbal during the same period, have a characteristic time scale of about 4$\sim$5 days. These variations could be interpreted as equatorial gravity waves. Using San Cristóbal and Singapore radiosonde data, Hasebe and Koyata (2002) pointed out that the upper tropospheric perturbations in temperature and wind are more active at San Cristóbal than at Singapore.

3.5 Ozone/RH layers observed at San Cristóbal and Watukosek

Layers similar to those shown in Figs. 5 and 6 are also observed at San Cristóbal and Watukosek. Figure 10 shows an example at San Cristóbal from the same season as the Shoyo-Maru campaign. The ozone profile shows strong layers, which are highly anticorrelated with structures in the RH profile, though there appears the slight mismatch in the vertical between RH and ozone as suggested in section 2. Furthermore, the northerly winds dominate in ozone poor and wet layers. No example at Watukosek can be shown, since the observations we used here did not include the humidity measurements.

Using the weekly ozonesonde observations at San Cristóbal, we can examine the seasonal cycle of these layers. To extract the layered structure, we apply a high-pass filter, in which we subtract the 2750 m (55 points) running mean from the original raw value at each level. The squares of these filtered profiles are averaged for each month and binned into 1 km intervals. The value derived with this procedure is an average of square, which we call "ozone variance", and is shown in Fig. 11. The basic feature in the seasonal and vertical distribution of variances is not sensitive to the filter design, though the variances become larger if we use the longer running mean. In all months, the ozone variances are larger in the upper troposphere with some enhancements in August

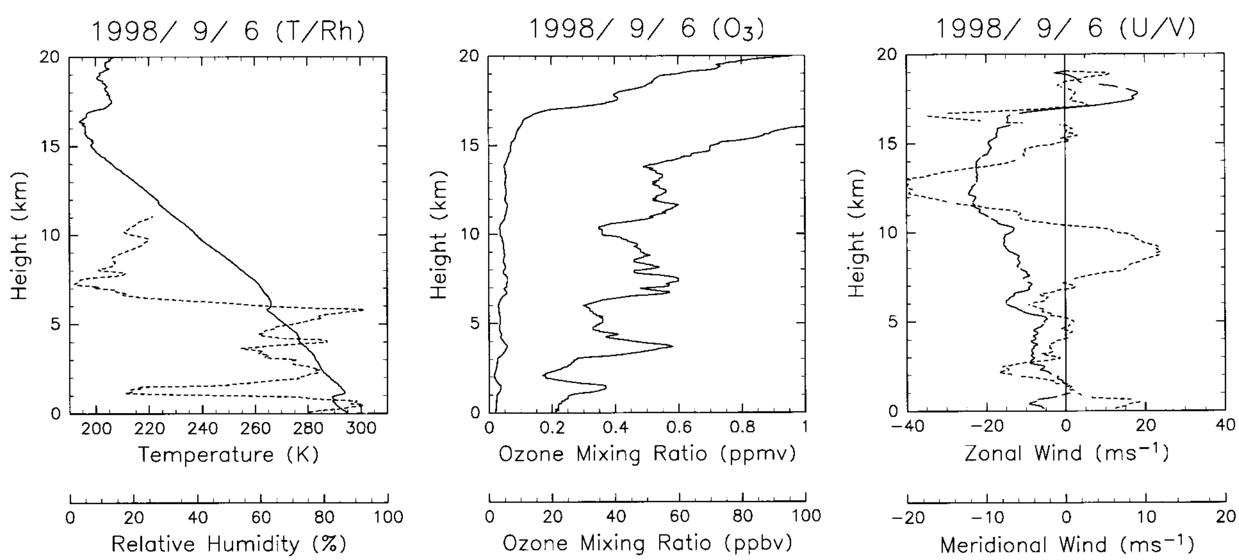

Fig. 10. Same as Fig. 5 for San Cristóbal, September 6, 1998.

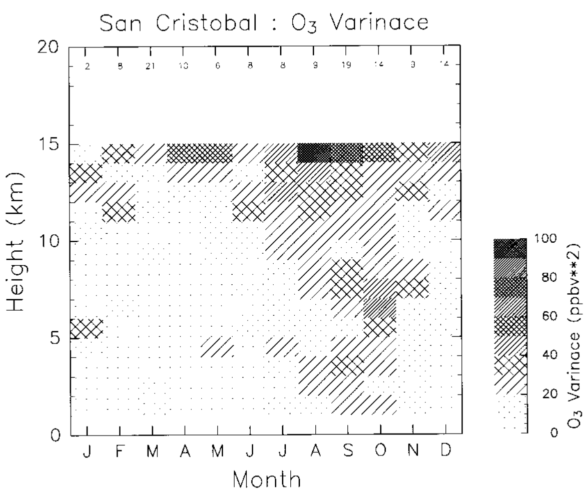

Fig. 11. Time-height cross-section of ozone variances at San Cristóbal using 1 km bins. The variance is defined as the monthly average of the high-pass filtered profile squared. The number of observations for each month is shown in the upper part of the figure.

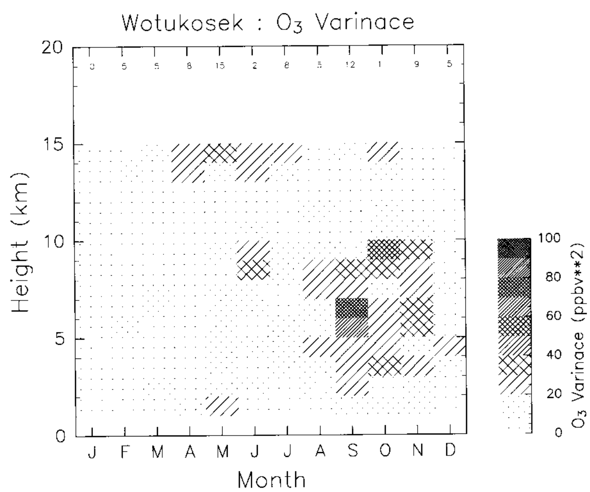

Fig. 12. Same as Fig. 11 for Watukosek.

and September. In the middle and lower troposphere the ozone variance is enhanced only during August to October, the local dry season, related to biomass burning in South America (Oltmans et al. 2001).

A similar analysis using ozonesonde data at Watukosek is shown in Fig. 12. Since the vertical spacing of the ozone profile is 4 times larger (200 m) than at San Cristóbal, the high-pass filter uses a 2600 m (13 points) running mean. Due to this different vertical resolution, only qualitative comparisons can be carried out. Large variances in the middle and lower troposphere are commonly observed at Watukosek during the local dry season (September to November). In the upper troposphere, however, an increase in the ozone variance at Watukosek is not as clear compared to San Cristóbal, which may be related to the higher altitude of the ozone increase at Watukosek.

The large variance in the uppermost troposphere may be due to equatorial waves such as Kelvin waves. Ozone enhancements due to Kelvin waves in the tropopause region were observed by Fujiwara et al. (1998, 2001) and studied using a general circulation model including simple ozone photochemistry (Fujiwara and Takahashi 2001). Another possibility for the upper tropospheric enhancements in ozone variance are isentropic intrusions into the tropical upper troposphere due to the planetary wave breaking (Waugh and Polvani 2000). In the middle and lower troposphere, large ozone variances were found during the local dry season, suggesting that less convective vertical mixing maintains the layered structures.

4. Summary

We presented results from the first shipbased sonde observations of ozone and meteorological parameters in the tropical eastern Pacific during September to October 1999. This survey was conducted as a part of the Soundings of Ozone and Water in the Equatorial Region (SOWER)/Pacific mission.

The mean profile of ozone resembles that for the same season at San Cristóbal, Galápagos (0.9°S, 89.6°W) and shows the following characteristics: Tropospheric ozone concentrations (40 ppbv on average) are enhanced in the mid-troposphere, which is most likely related to biomass-burning origin (Fujiwara et al. 1999, 2000; Oltmans et al. 2001). The increase of ozone below the tropopause is gradual compared to Watukosek, suggesting that the lower boundary of the TTL depends on season and geographic location, due to differences in convective activity. The amount of ozone in the marine boundary layer is very small, indicating effective ozone destruction in the marine boundary layer in the eastern Pacific.

During the cruise we observed layers in ozone and humidity profiles which are highly anticorrelated, with typical vertical scales of a few kilometers. With use of the regular GPS sonde profiles we have confirmed that these layers can persist on horizontal scales of about 1000 km or time scales of about 2 days. They are related to northerly winds bringing in wet and ozone poor air from the ITCZ about 5° to the north of the main cruise track (2°N). The wet and ozone-poor outflow from the convective systems seems to be essential to the layered structures. The vertical distribution of these layers may be due to convective cloud systems with a different cloud top heights or due to multiple outflows from one convective cloud system.

We also observed such layered structures in ozonesonde profiles at San Cristóbal and Watukosek. From a statistical analysis we quantified the seasonal cycle of these layered structures using ozone variances. At San Cristóbal the ozone variances are larger in the upper troposphere year round, and in the middle and lower troposphere during the local dry season in August through October. At Watukosek characteristic features are very similar compared to San Cristóbal, except that the upper tropospheric variances are not as large. Larger and more variable ozone concentrations in the upper troposphere may be related to wave activity such as Kelvin waves (Fujiwara et al. 1998, 2001) or Rossby waves (Waugh and Polvani 2000). The large ozone variances in the middle and lower troposphere during the local dry season support the idea that the layers are advected without vertical mixing. We speculate that the layers are widespread in the relatively quiet region of the equatorial Pacific, where convective activity is suppressed. The tropical troposphere in the cruise region can be viewed as a series of layers, stacked in the vertical. The wet and low ozone layers might be originated from the ITCZ; the dry and high ozone layers possibly affected by biomass burning from the mid-latitudes or due to convection aloft with subsequent sinking.

Acknowledgments

We gratefully acknowledge Capt. K. Kubota, K. Ohshima, S. Sawadaishi and the Shoyo-Maru crew members who helped our observations. We thank two anonymous reviewers for helpful comments and suggestions, K. Kita, University of Tokyo for providing some instruments of ozone observations and N. Nishi for stimulating discussions. The ozonesonde observation at Watukosek has been operated by

LAPAN, Indonesia and EORC/NASDA, Japan; recently it has been partially supported by the SHADOZ project. Graphic outputs were made by use of the GFD-DENNOU Library. This work was supported in part by the Grant-in-Aid for Scientific Research of Priority Areas (B), No. 11219201.

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