Dynamical Properties of the Tropical Atmosphere Derived from Radiosonde Observations at San Cristóbal and Singapore

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Abstract

Operational radiosonde data at San Cristóbal (0.90°S, 89.62°W; eastern Pacific) are compared with those at Singapore (1.37°N, 103.98°E; western Pacific) intending to explore the differences in the dynamical properties of the tropopause region and in the activities of atmospheric waves between the eastern and the western tropical Pacific. The interannual variations in the meteorological parameters of the tropopause region are found to be almost synchronized between the two stations and do not show direct correspondence with the time evolution of El Niño. These evidences, as opposed to the general expectation of the strong influence of sea surface temperature variations on the tropopause properties, suggest that the tropospheric dynamical forcing is not a prevailing factor that drives the interannual variation of the tropical tropopause properties for these stations. The dynamical parameters of the tropopause region are affected by passages of vertically propagating atmospheric waves that characterize the time evolution of daily sounding data. The variations with the time scales of 15 to 20 days are identified as equatorial Kelvin waves of zonal wave number 1, which is consistent with the observed out-of-phase relationship between the two stations. The perturbations in the tropospheric temperature and wind are also brought about by those waves with the typical time scales of several days. These waves are more pronounced over San Cristóbal than in Singapore. As the convections are more active and reach higher altitude in the western than in the eastern Pacific, this evidence implies that the altitude rather than the strength of convection is more important in characterizing the daily fluctuations of the tropical troposphere. The differences between the two stations in the time evolution and magnitude of the quasi-biennial oscillation in the equatorial stratosphere are found to be marginal, although occasional differences in the onset time and the magnitude of zonal wind acceleration could be pointed out.

1. Introduction

It is generally believed that the stratospheric ozone layer has been shielding life on earth from hazardous components of the solar ultraviolet radiation since the rise of the atmospheric oxygen concentration at a relatively early stage of planetary evolution. The absorption of solar radiation leads to in situ heating in the upper atmosphere, creating a convectively stable layer named the stratosphere. In the lowermost atmospheric layer, the troposphere, the primary heating comes from the absorption of radiation at the lower boundary, the surface of the earth. Thus the troposphere is essentially unstable with respect to the thermal structure and is characterized by active convection. The boundary between these two contrasting layers is the tropopause.

The mechanism fundamental for the maintenance of the tropopause, that is, how its altitude and temperature are determined, is not yet fully understood. Since the stratospheric

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humidity is controlled by the freeze-drying mechanism taking place on the passage of tropospheric air through the tropical tropopause (Brewer 1949), dynamical processes that control the exchange between the tropical troposphere and the stratosphere, have also attracted much scientific interest (e.g., Highwood and Hoskins 1998).

Early investigations on the tropical tropopause were more or less concerned with the tropospheric convective processes. The seasonal variations of the height and temperature of the tropical tropopause were investigated by Reid and Gage (1981), who showed that the tropopause is higher and colder in Northern Hemisphere winter (NW) than in summer (NS) and argued that such a seasonal cycle could be understood as a reflection of the tropospheric forcing by the convective activities below. Newell and Gould-Stuart (1981) pointed out that the tropopause temperature averaged in the tropics is too high to explain the observed dryness of the stratosphere, and proposed the "stratospheric fountain" hypothesis in which the entry of the tropospheric air must be restricted to tropical western Pacific during boreal winter and the Bay of Bengal in summer where tropopause temperature is cold enough so as not to introduce discrepancy with stratospheric dryness. However, Sherwood (2000) shows that the vertical motion near the tropopause over the western Pacific is downward. This finding is supported in a numerical simulation made by a general circulation model (Hatsushika and Yamazaki 2001).

The active convection in organized convective system occasionally overshoots the tropopause and penetrates into the stratosphere. The understanding of such processes has been one of the key issues in the study of the troposphere-stratosphere exchange in the tropics, and has prompted organizing campaigns such as the Water Vapor Exchange Experiment around Panama, and the Stratosphere-Troposphere Exchange Project in the western tropical Pacific. Danielsen (1982) pointed out the importance of irreversible mixing of tropospheric and stratospheric air associated with the overshoots at the top of the tropical anvil cloud system. Kley et al. (1982) observed that the local penetration of the cumulonimbus clouds over Panama could hydrate the stratosphere, while the hygropause, as defined by the local minima of the water vapor mixing ratio, is situated a few kilometers higher than the local tropopause. This result is interpreted as being consistent with the "stratospheric fountain" hypothesis, suggesting the existence of some entry point of the tropospheric air somewhere distant from Panama.

On the other hand, it is widely accepted that the extratropical wave drag is influencing the equatorial upwelling (Haynes et al. 1991; Holton et al. 1995), although more arguments are still necessary to explore the latitudinal extent of the pumping effect and the renewed role of diabatic heating (Plumb and Eluszkiewicz 1999). Yulaeva et al. (1994) indicated that the seasonal cycle of the tropopause temperature could be brought about by the modulation of the extratropical suction pump. The evidence of the dehydration associated with the passage through tropical tropopause has been shown imprinted in the vertical profile of water vapor mixing ratio (Mote et al. 1996). The signal, recorded by the "tape recorder" at the tropical tropopause, has been used to measure the mean vertical velocity in the tropical lower stratosphere. This result is consistent with the previous estimates of the air mass flow derived indirectly by using the residual circulation (Rosenlof and Holton 1993). Careful examination of this signal has made it possible to estimate the modulation of the vertical motion induced by the quasi-biennial oscillation (QBO) of the equatorial zonal wind (Niwano and Shiotani 2001).

Recent investigation by Highwood and Hoskins (1998) emphasizes the existence of the tropical transition layer (TTL) introduced by Atticks and Robinson (1983). According to their idea, the tropical tropopause is now not a clearly defined boundary between the troposphere and the stratosphere but instead should be treated as a transition layer extending from around the 200 to 80 hPa levels. This layer is located above the reach of tropospheric deep convection but below the tight control of the extratropical suction pump, thus dividing the two major dynamical processes that could affect the tropical tropopause.

In order to understand the dynamical processes taking place in the TTL, it is quite important to consider the influence of atmospheric waves. Tsuda et al. (1994) made a detailed analysis of the dynamical properties of the tropical tropopause region based on a series of radiosonde soundings in Indonesia. They suggested an important role for the equatorial and gravity waves on the atmospheric exchange between the troposphere and the stratosphere. Fujiwara et al. (1998) showed that the upper tropospheric ozone variation is related to the vertical transport of the stratospheric ozone associated with equatorial Kelvin waves and irreversible mixing accompanied by the breaking of such waves at the vicinity of the tropical tropopause. There is also some evidence for such waves to control the water vapor budget in the TTL (Fujiwara et al. 2001). Thus, the tropical tropopause region is quite interesting in both the mechanisms of its formation and variation, and its role in controlling the mass and tracer exchange between the troposphere and the stratosphere.

In dealing with the detailed atmospheric processes in the TTL, one should also be aware that there is a longitudinal inhomogeneity in the tropical region. The equatorial Pacific is characterized by the existence of the east-west oriented Walker circulation. It is an atmospheric manifestation of the equatorial atmosphere-ocean system that is responsible for driving the El Niño. Due to this circulation, there appears a strong contrast in the climatic conditions between the eastern and the western Pacific. That is, the western Pacific is characterized by active convection associated with high sea surface temperature (SST), while in the eastern Pacific the convection is more or less suppressed due to relatively low SST and the predominant sinking motion of the Walker cell. In fact, the tropical tropopause temperature shows an east-west dipole pattern and north-south oriented dumbbell-shaped anomalies (Randel et al. 2000; Zhou et al. 2001) in response to the tropospheric temperature changes with respect to SST forcing (Yulaeva and Wallace 1994).

In order to understand the dynamical properties of the tropical atmosphere, it is quite interesting to investigate the longitudinal structure of the meteorological properties in the tropical tropopause region. Since the vertical scale of the waves could be less than several kilometers at the vicinity of the tropopause, the current satellite observations are unable to resolve these phenomena. In the present study, the radiosonde data at San Cristóbal, Galápagos, that have not yet been described in the literature, are analyzed by comparing them with those at Singapore with emphasis on the east-west contrast of the dynamical properties along the tropical Pacific. The representativeness of these stations from the viewpoint of climatic conditions will be discussed by referring to the studies already appeared in the literature. We will also speculate on the structure of the equatorial QBO which is supposed to be uniform along the equator.

The data quality control procedure is described in section 2. The results are presented in section 3 under the subjects of the annual cycle and the interannual variations in tropopause characteristics, the daily variations in temperature and wind, and the QBO in zonal wind. These results are discussed in section 4. Concluding remarks are placed in section 5.

2. Data

The data used in the present study are those from the operational radiosonde observations at San Cristóbal, Galápagos (0.90°S, 89.62°W) and Singapore (1.37°N, 103.98°E) compiled by the National Climate Data Center (NCDC) at Asheville, NC, U.S.A. The soundings are made only once a day at San Cristóbal, while twice or four times a day at Singapore. The altitude coverage, limited mostly by balloon's burst, is slightly restricted to lower altitudes at San Cristóbal than at Singapore. In general, the profiles of temperature, geopotential height, relative humidity, dew point temperature, and the direction and speed of wind are available below about 10 hPa corresponding to about 32 km from the surface. Each profile consists of the records at the so-called mandatory levels and the significant levels. The tropopause defined by the WMO criterion has been identified for each profile by the data provider. In the present study, only the temperature, geopotential height, and wind field are analyzed. The data currently available to us cover those periods from 1991 to 1993 for San Cristóbal and from 1981 to 1995 for Singapore.

The data provided from NCDC have already been treated with intensive data quality control procedure. However, they are not ready to be used in the present study. For example, there are some cases where a few different values are given at the same pressure level from a single sounding. In such cases, careful examination has been made for each profile, and the value regarded as most reasonable has been chosen after consideration of the smoothness in both the vertical profile and the time evolution. For those cases where data are apparently mishandled during the editing procedure, they have been rejected before putting them through any statistical tests. For example, the specifications as the tropopause have been ignored if they are located above 40 hPa or below 200 hPa. After performing the initial screening procedure, the time sequence of profiles has been examined by paying special attention to continuity in the time domain. In case the geopotential height is missing, it is calculated from the temperature data at given pressure levels using the hypsometric equation. However, those cases in which temperature data are too sparse, the geopotential height is taken to be missing.

Additional data screening procedures have been applied for deriving the statistical properties of the tropopause. These are described in the corresponding section. The average profiles, where needed, have been derived by linearly interpolating the data into the pressure levels regularly distributed in log-pressure coordinates. They are defined by

$$p_i = 10^{3-i/250} \quad (i = 0, 1, \ldots, 500)\ \text{hPa}. \tag{1}$$

No extrapolation has been attempted above the ceiling of each sounding. The resultant vertical resolution is about 64 m corresponding to 10 to 13 seconds in the time interval during the sonde ascents. This resolution would enable us to capture any vertical structure in the original data without distorting minute characteristic features in each profile.

3. Results

3.1 Annual cycle in the tropopause properties

The tropopause is usually defined as the lowest atmospheric region that satisfies the condition that the temperature lapse rate of less than 2 K km^{-1} continues for at least 2 km of altitude range. This definition, hereafter referred to as the lapse rate tropopause (LRT), is conveniently applied to any atmospheric condition encountered over the globe. In the tropics, especially in dealing with the water vapor transport between the troposphere and the stratosphere, however, the atmospheric layer with lowest temperature along the profile, hereafter the cold point tropopause (CPT), will be more important. From this standpoint of view, we could be more strict if we consider the atmospheric condition exhibiting the lowest value of the saturation mixing ratio of water vapor. As the sounding data are available only on the significant levels (in addition to standard levels) where temperature takes minima or maxima, however, it is hard to identify such altitude from the current data. In this analysis, the features of both the LRT and CPT will be discussed.

Figure 1 shows the scatter diagrams between two variables among pressure, geopotential height, and temperature of the LRT. The left column corresponds to those for San Cristóbal, while that on the right is those for Singapore. Before making meteorological analysis, it is necessary to remove possible eccentric data (e.g., those with the tropopause altitude above 20 km). The following procedure has been taken to remove such data and improve statistical homogeneity in each of the datasets at the two stations. Those expressed by crosses ($\times$) in the figure cleared the following data screening procedure, while those shown in dots ($\cdot$) did not:

1. the ensemble mean, m, and the standard deviation, σ, of the logarithmic value of tropopause pressure are calculated;
2. those data outside 3σ are removed. That is, i-th data with tropopause pressure p_i is removed if

$$|\ln p_i - m| > 3\sigma \quad (i = 1, 2, \ldots, n), \tag{2}$$

where

$$m = \frac{1}{n}\sum_{i=1}^{n} \ln p_i, \quad \sigma = \left\{\frac{1}{n-1}\sum_{i=1}^{n}(\ln p_i - m)^2\right\}^{1/2}; \tag{3}$$

3. this 3σ criterion is applied repeatedly to the remaining set of data until no data is removed in a single step;
4. a regression line of geopotential height against log-pressure is calculated by the method of least square. The 3σ criterion with respect to this fitting line is applied. That is,

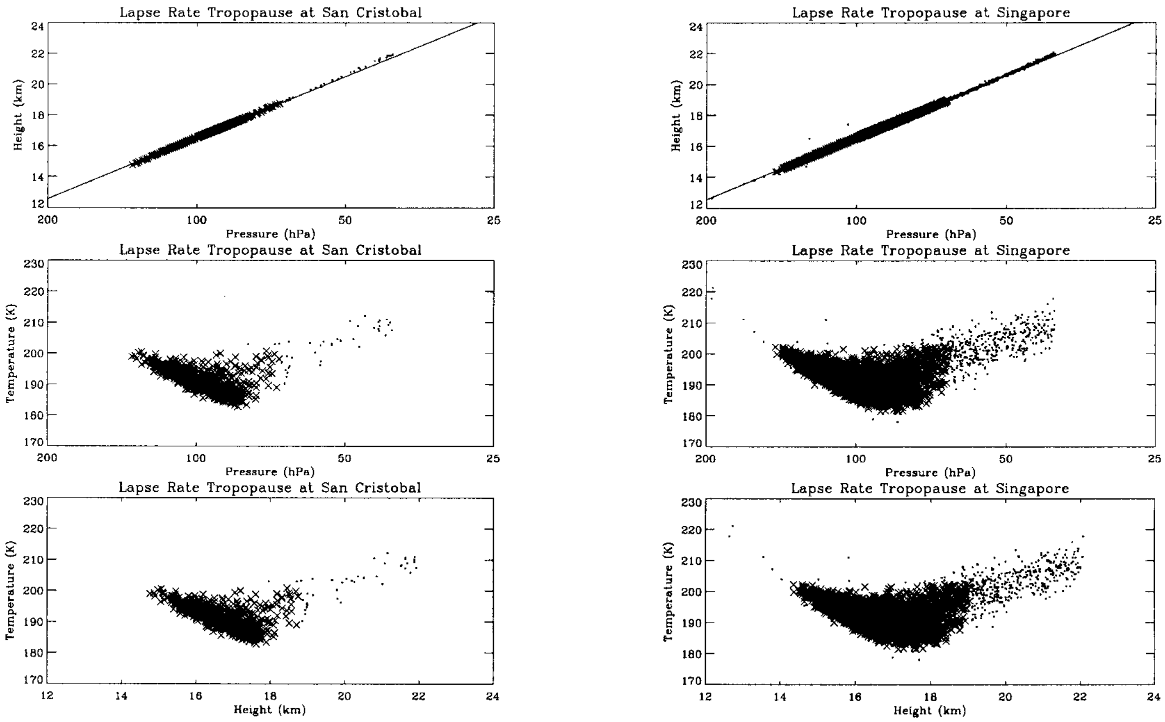

Fig. 1. Scatter diagram of the tropopause parameters for (left) San Cristóbal and (right) Singapore. Those expressed in crosses ($\times$) are accepted while those in dots ($\cdot$) are rejected after data screening. See text for the details.

i-th data with pressure p_i and geopotential height Z_i is removed if

$$|Z_i - (a \ln p_i + b)| > 3\sigma' \quad (i = 1, 2, \ldots, n'), \tag{4}$$

where a and b are the coefficients of the regression equation, and σ' is defined by

$$\sigma' = \left[\frac{1}{n'-1}\sum_{i=1}^{n'}\{Z_i - (a \ln p_i + b)\}^2\right]^{1/2}; \tag{5}$$

and,

5. the 3σ criterion with respect to temperature is finally applied to the data that survived the above procedures.

The monthly mean values of log-pressure, geopotential height, and temperature of the LRT are calculated for each station using the dataset that cleared the data screening procedure described above. The results are presented in Fig. 2, that shows the seasonal variation of the monthly mean values of the above variables for San Cristóbal on the left and Singapore on the right. The comparison is made for 1991, 1992, and 1993 by illustrating in solid, dotted, and dashed lines, respectively. The vertical bars, slightly shifted along the abscissa by each year for the sake of visual clarity, indicate the range of one standard deviation during the month for each variable. Noticeable features may be:

1. the well known seasonal variation of the tropical tropopause (Reid and Gage 1981) is commonly seen at both stations. That is, the tropopause is higher and colder during NW, while it is lower and warmer in NS;
2. the seasonal variation in 1991 appears to be exceptional at both stations. From January to June, the tropopause is found at altitudes much lower than those for 1992 and 1993, so that the tropopause at Singapore moved upward from January to May, in contrast with the general descending tendency in the corresponding season of the year;
3. there is no clear tendency that the tropopause is higher and colder in Singapore than in San Cristóbal. Tropopause temperature is even colder in San Cristóbal than in Singapore from December 1991 to April 1992; and,

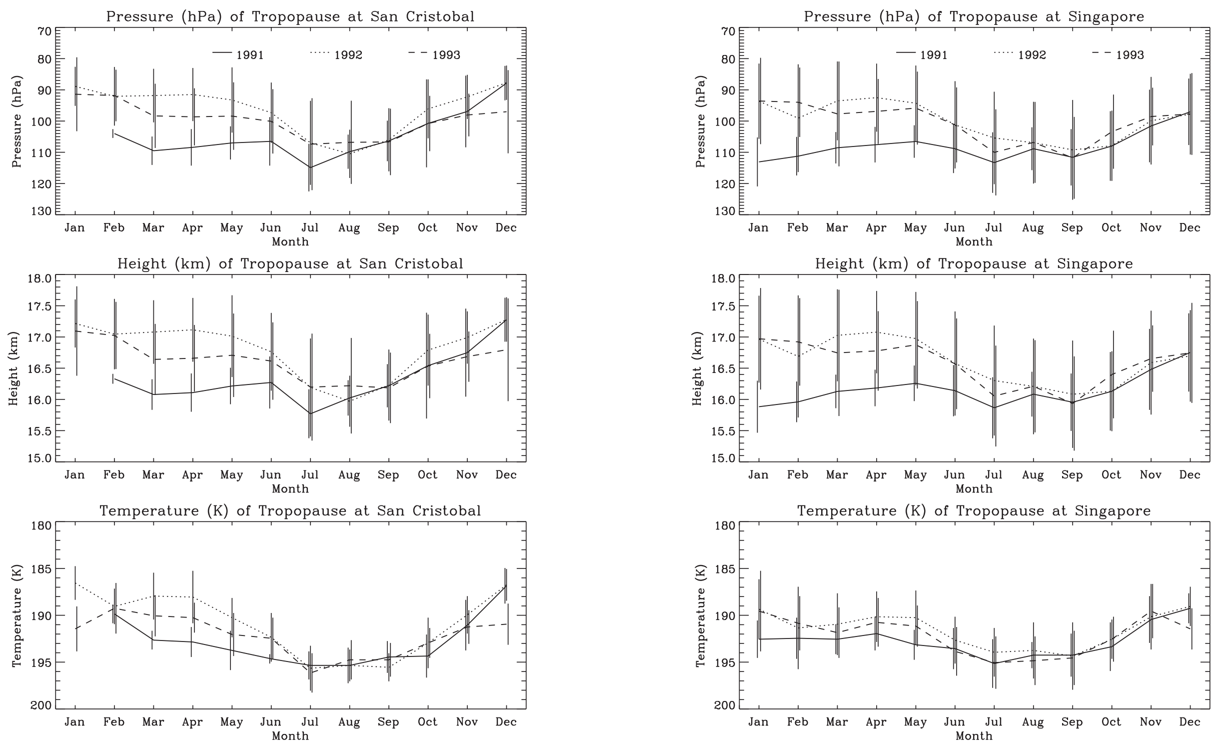

Fig. 2. Time series of the monthly mean values of (top) tropopause pressure, (middle) tropopause height, and (bottom) tropopause temperature at San Cristóbal to the left and Singapore to the right. The error bars are 1 standard deviation for each month of (left) 1991, (center) 1992, and (right) 1993.

4. the modification of the seasonal cycle in 1991, 1992, and 1993 is qualitatively the same for both stations. The synchronized behavior at San Cristóbal and Singapore suggests that the east-west contrast in the tropospheric forcing is not a primary factor that modulates the seasonal variation of the tropopause properties.

Similar comparison is made for the statistical compilation of CPT. To avoid possible bias from the soundings terminated at lower altitudes, only those soundings that provided data as high as 70 hPa are used. The results are shown only for the temperature in Fig. 3. Although the basic features for the seasonal variation remain the same as those for LRT, some of the points mentioned above need to be modified:

1. the features of the seasonal variation become more pronounced by investigating CPT than LRT;

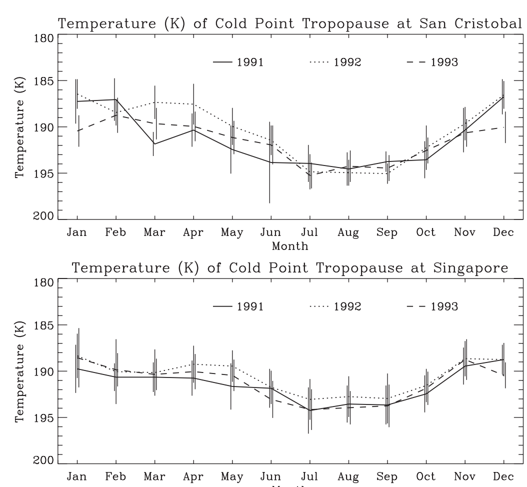

Fig. 3. Similar to Fig. 2 but for the temperature of cold point tropopause.

2. 1991 is no longer exceptional in terms of the seasonal variation if those features of CPT are considered;
3. the east-west contrast between the two stations does not come out also for the case of CPT. The temperature tends to be lower in December–February and higher in July–August in San Cristóbal than in Singapore, making the amplitude of the annual cycle larger in the former than in the latter; and,
4. the synchronization between the two stations in the interannual variations still holds for CPT.

Some of these points will be discussed in section 4.

3.2 *Interannual variations in tropopause properties*

The interannual variations of those variables that characterize the tropopause region are considered. To avoid redundancy, only the results for the CPT are shown. Figure 4 shows the time series of log-pressure, geopotential height, and temperature of the CPT. The thin lines with error bars are the variations at Singapore, while the squares connected with thick lines without bars are those at San Cristóbal. As was shown in the previous subsection, there is a close correspondence between the variations at the two stations. From the longer record in Singapore, some long-term variations are seen in those features with time scales of two to several years. The behavior is almost similar between the features of the LRT (not shown) and CPT except for the period from late 1989 to early 1991 when the seasonal variation is mostly suppressed in the record of LRT features (Fig. 2).

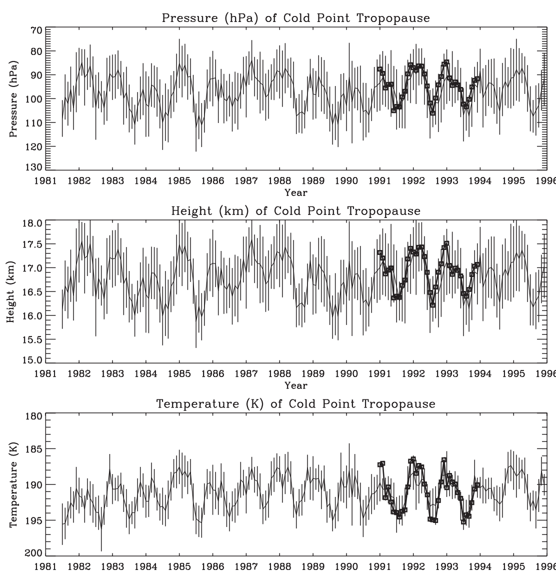

Fig. 4. Time series of the monthly mean values of (top) pressure, (middle) height, and (bottom) temperature of the cold point tropopause at San Cristóbal (squares connected with heavy lines) and Singapore (thin lines). The error bars are 1 standard deviation for each month at Singapore. Those bars are omitted for San Cristóbal for visual clarity.

In spite of the difficulty in defining a climatology from the data that cover only three years in San Cristóbal, a removal of the mean annual cycle is attempted for each station by subtracting the mean values for each calendar month from the raw values of the corresponding month in the time series. In the estimation of the mean annual cycle, all available monthly mean values have been used. The results for Singapore remain almost the same if the mean values of 1991, 1992, and 1993 are used to define the climatology (not shown).

The time series of the anomalies as defined by the deviation from the mean annual cycle for the features of CPT are shown in Fig. 5. The top three panels correspond to the anomalies of those shown in Fig. 4, while the bottom shows the deseasonalized and normalized Southern Oscillation Index (SOI), which is defined by the difference in the sea level pressure at Darwin and Tahiti. Instead of the seesaw behavior between the variables at San Cristóbal and Singapore, the anomalies are almost in phase between the two stations. The fact that they do not show a clear relationship with the SOI is also beyond our expectations. The meanings of these findings are discussed in section 4.

3.3 *Daily sequence of temperature and wind profiles*

The day-to-day variations of the temperature and wind fields are quite interesting given the important role of equatorial and gravity waves in driving the QBO in the equatorial stratosphere (e.g., Baldwin et al. 2001) and on exchanging the stratospheric and tropospheric air

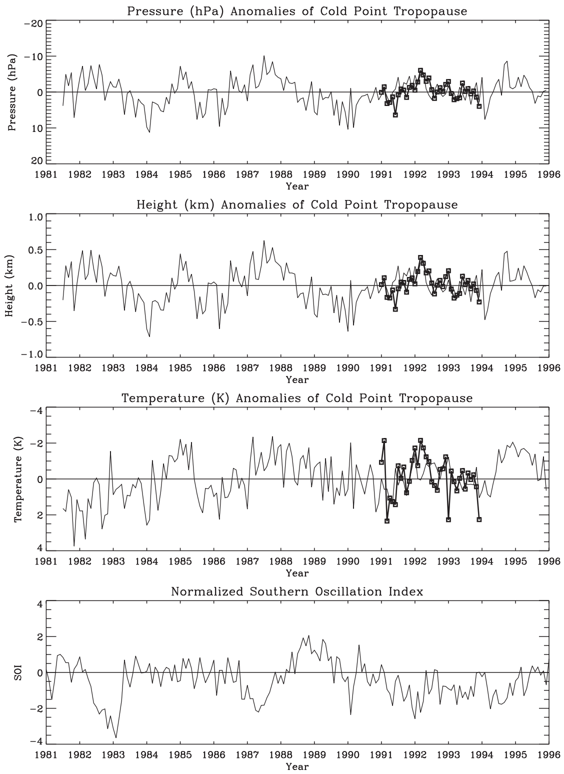

Fig. 5. The upper three panels are the same as Fig. 4 except that the anomalies of the cold point tropopause are shown. The bottom panel shows the deseasonalized and normalized Southern Oscillation Index.

including minor constituents such as ozone across the equatorial tropopause (Fujiwara et al. 1998). Here, an attempt is made to shed light on the characteristics of the day-to-day variations of temperature and wind profiles at San Cristóbal and Singapore by using the radiosonde observations. The data at San Cristóbal are for 12 UT. In Singapore, two to four observations a day are available in the original dataset, among which those at 00 UT are chosen, as the missing data are least frequent and the best altitude coverage is attained. Due to the near correspondence of local time at the two stations (6 O'clock in San Cristóbal and 7 in Singapore), the effect of possible diurnal variations could be minimal.

The wind direction and speed in the original datasets are converted into zonal and meridional wind velocity components. Then the wind velocity components, together with temperature, are linearly interpolated to the gridpoints regularly spaced with respect to log-pressure as described in section 2. This interpolation procedure has been applied to all data available. However, the daily sequences are examined only for the 36-month period from January 1, 1991 to December 31, 1993 since missing observations are rather frequent in either or both stations during other periods of the analysis. The results are shown only for one-year period from January to December, 1992 in Fig. 6. The top two panels show the time sequence of temperature profiles at San Cristóbal and Singapore, drawn by shifting to the right hand side of the diagram corresponding to the day of the year. The middle and the bottom panels are the same as the top, except that the zonal and meridional wind components, respectively, are illustrated. Due to smaller balloons used, the soundings at San Cristóbal are almost always terminated around 20 hPa level, while those at Singapore reach 10 hPa with only a few exceptions.

Among many features recognized from these figures, our analysis is concentrated to those having some coherent structures such as the following:

1. Temperature perturbations: day-to-day variations in temperature are more pronounced in the stratosphere; there appears some difference in the properties of time evolution between the upper and the lower troposphere; and, the amplitude is larger in San Cristóbal than in Singapore.
2. Daily variations of the CPT pressure and temperature: it is readily seen that the fine structure of the temperature profile around CPT is strongly affected by the waves propagating in the vertical direction with the typical time scales ranging from several to 20 days; that is, CPT is higher and colder when the cold phase of the prominent wave coincides with the climatological mean CPT; and, on its passage through the tropopause region, the altitude of CPT shows an abrupt jump after the gradual descending motion, as pointed out by Tsuda et al. (1994).
3. Stratospheric zonal wind: there appears a gradual descent of the easterly regime of the QBO in the stratosphere; the easterly

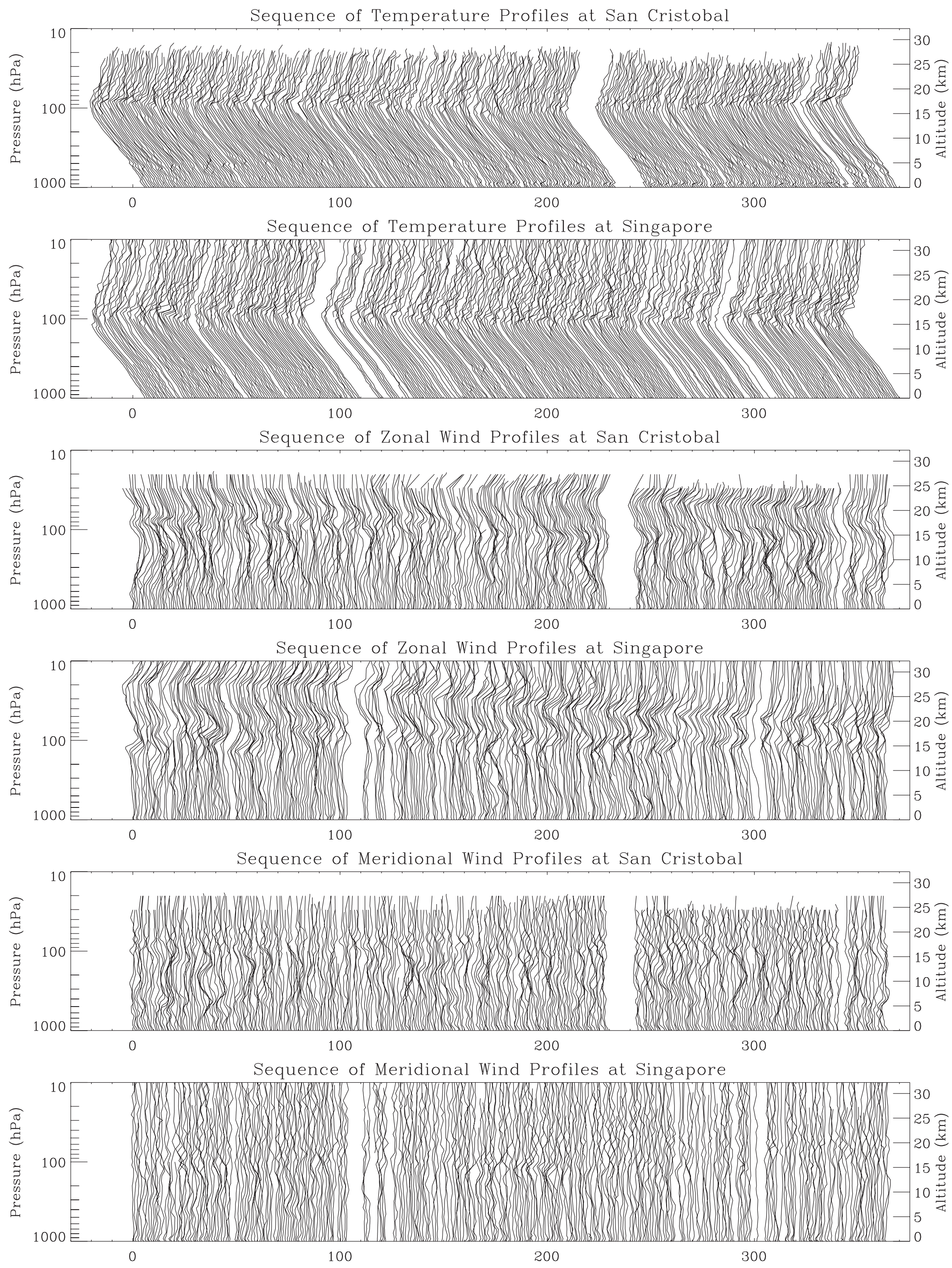

Fig. 6. Sequences of profiles for temperature and zonal and meridional wind velocity components observed by sondes at San Cristóbal and Singapore in 1992. The two panels at the top correspond to temperature profiles at San Cristóbal and Singapore. Two panels in the middle and the two at the bottom are the same as the top two except for the zonal and the meridional velocity components, respectively, are illustrated. The tick marks on Day 0 correspond to 0°C for temperature and 0 m s^{-1} for wind on January 1.

wind maximum propagates downward from 20 hPa on around Day 0 to 70 hPa on Day 360; the warm anomaly associated with the westerly shear just above the easterly maximum of zonal wind QBO is recognized; and, the phase speed is relatively low during NW (till about Day 100) while the propagation is accelerated in NS, probably reflecting the seasonal variation of the equatorial ascending motion.

4. Daily perturbations in wind field: gross features of the fluctuations could be seen as a pattern of light and shade in the diagram; the perturbations having relatively long time scales, with period of 15 to 20 days, are stronger in the zonal wind component than in the meridional; these perturbations are more or less confined around the altitude region above the tropopause in Singapore, while they are noticeable even in the troposphere in San Cristóbal; and, for the meridional wind component, the variabilities with relatively short time period, approximately 3 to 7 days, prevail.

In order to explore the characteristic features of these atmospheric waves in more detail, it is convenient to apply time filtering to separate each component as was done in Shiotani and Horinouchi (1993) and Tsuda et al. (1994). For this purpose, linear interpolation has been applied in the time domain to produce time series sampled with a regular time interval of one day at constant pressure levels. Characteristic time scales are sought by applying power spectral analyses to the time series partitioned into pieces of data with a length of 128 ($= 2^7$) days and taking the average of the spectrum obtained from the whole time series. Among several spectral peaks resolved (not shown), our analysis is focused on those variations having the typical time scales longer than about 10 days and those between 3 and 7 days. These two domains correspond to those analyzed by Shiotani and Horinouchi (1993). In the present analysis, a low-pass filter is employed and a band-pass filter is used to see long-term and short-term variations, respectively. The frequency response functions for these filters are shown in Fig. 7. See Hasebe (1980) for the design of these filters.

Figure 8 shows the time-height section of the

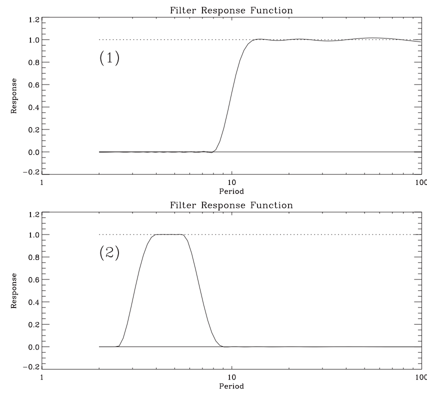

Fig. 7. Frequency response function of the time filters.

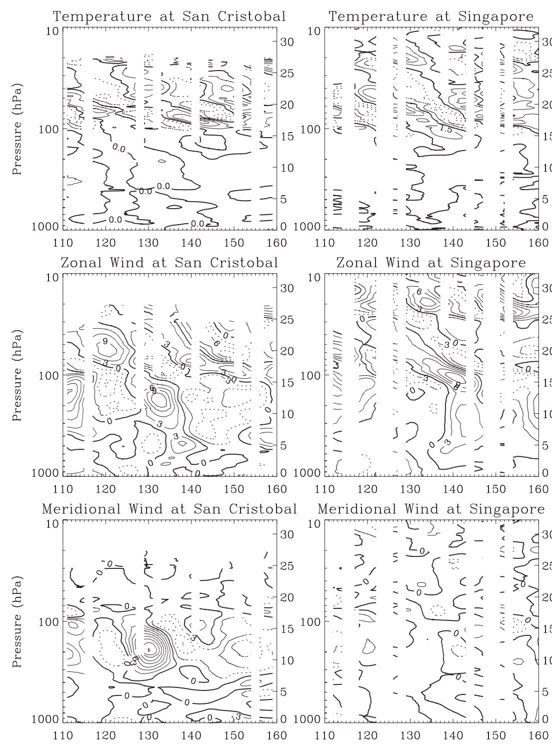

Fig. 8. The time height section of the low-pass filtered (top) temperature, (middle) zonal wind and (bottom) meridional wind anomalies at San Cristóbal (left) and Singapore (right). The contour intervals are 1.5 K and 3 m s^{-1} for temperature and wind, respectively. Dashed contours correspond to negative values.

low-pass filtered temperature, zonal wind and meridional wind at San Cristóbal and Singapore from Day 110 to 160 in the year 1992. Missing data in the original time series are omitted in the illustrations, although interpolated values are used in time filtering. For the sake of clarity, the mean values during this 51-day period are subtracted for each pressure level. Noticeable features are:

1. in the lower stratosphere, the variations with period of about 15 to 20 days appear in the temperature and zonal wind, while they are mostly missing in the meridional wind. The phase in temperature precedes that of zonal wind by about a quarter cycle exhibiting downward propagation. The oscillations at San Cristóbal and Singapore are out-of-phase. The downward phase speed is roughly 1 km per 3 days below 20 km, corresponding to -4×10^{-3} m s^{-1} and vertical wavelength of about 6 km, although some difference may appear in zonal wind at San Cristóbal. The altitude with maximum wave amplitude shows gradual ascent. In Singapore, for example, the maximum in temperature perturbations located around 80 hPa (18 km) on Day 133 reaches 50 hPa (21 km) on Day 142. This gives an estimate of the ascending velocity of 4×10^{-3} m s^{-1}. The corresponding perturbations in zonal wind may possibly be traced from the maximum at 16 km on Day 141 to the minimum at 18 km on Day 143. This will give an alternative value of 1×10^{-2} m s^{-1}. If the perturbations could be treated as a wavepacket, these values will give estimates of the vertical group velocity of the wave. See section 4.2 for discussion on wave parameters; and,
2. in the troposphere, the variations are generally small especially in Singapore. There appear westerly perturbations around Day 143 in Singapore. However, the phase lines are aligned almost vertically in contrast to those in the stratosphere. In San Cristóbal, the fluctuations occasionally reach large amplitude both in zonal and meridional winds. A peculiar event of large meridional wind perturbations around 200 hPa on Day 130 is brought about by an intermittent oscillation of meridional wind that shows a rapid growth of southerly wind from May 8 (-1.3 m s^{-1}) to May 12 (29.4 m s^{-1}) and turning to the northerly (-16.9 m s^{-1}) on May 15. Although the gradient of the phase line is sometimes similar to that in the stratosphere, the fact that the waves have a meridional wind component, with magnitude similar to that in zonal wind, is a marked difference.

The relationship of these waves with the zonal wind QBO are examined in the next subsection.

The time-height sections for the variations, band-pass filtered with the period of about 5 days, are shown in Fig. 9. The time interval covered by the diagram is for three weeks from Day 205 to 225 in 1992. Important features may be summarized as the following:

1. the variations are almost always seen in temperature with the maximum amplitude

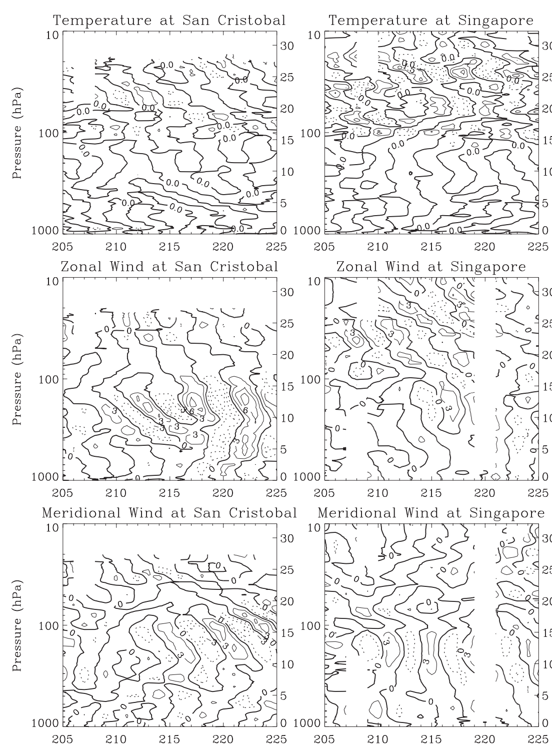

Fig. 9. Similar to Fig. 8 except that the band-pass filter with the period between 3 and 7 days is applied. Note that the time span is different from that of Fig. 8.

in the lower stratosphere. The amplitude in the stratosphere is larger in Singapore than at San Cristóbal, while the situation is reversed in the troposphere;

2. in the stratosphere, the downward phase propagation is relatively well described at San Cristóbal, while at Singapore the signal is rather noisy in temperature and weak in meridional wind. For all that, one could determine typical values of the wave parameters common to both stations such as about -1.5×10^{-2} m s^{-1} for the phase velocity, with the vertical wavelength of about 6 km. The phase of temperature precedes that of zonal wind by a quarter cycle; and,
3. in the troposphere, perturbations are appreciably larger in San Cristóbal than at Singapore. The phase lines are mostly tilting at San Cristóbal, while they are almost standing at Singapore. It appears that many waves are superposed to form the observed wind perturbation field. In contrast to the 15-day component, there is no clear anisotropy in the wind direction for these waves. That is, the magnitude of the oscillation is similar between zonal and meridional wind components. The upper tropospheric zonal wind field before Day 215 is characterized by the wave with the phase velocity of about -2×10^{-2} m s^{-1} and vertical wavelength of 8 km. After Day 217 the phase lines are bent at around 9 km altitude indicating bidirectional propagation with the phase speed of $\pm 4 \times 10^{-2}$ m s^{-1} and wavelength of 15 km. If these variations are interpreted as single waves, these features suggest that the energy source of the waves are located at around 9 km.

3.4 The quasi-biennial oscillation in zonal wind

It is generally believed that the QBO in the equatorial stratospheric zonal wind is driven by the interaction between equatorial and gravity waves and the mean zonal wind as originally proposed by Lindzen and Holton (1968) and Holton and Lindzen (1972). Since then, theoretical studies including realistic simulation of the QBO in general circulation models (e.g., Takahashi and Boville 1992) have contributed much to the improvement of understanding on the QBO. However, the question on the zonal symmetry of the QBO has not been challenged observationally since the work by Belmont and Dartt (1968) in the very early stage of the QBO research. In most cases, the monthly mean zonal wind speed at Singapore has been treated as if it were a zonally averaged value.

In the previous subsection, it has been seen that the wave activities supposed to be responsible for generating the QBO are different in San Cristóbal and Singapore. There is also a possibility that planetary scale stationary waves could penetrate into equatorial latitudes to produce time dependent bias in the zonal wind speed at a fixed location as shown by satellite wind data above 30 km (Ortland 1997). It is thus interesting to explore possible inhomogeneities of the zonal wind velocity associated with the QBO along the equator. Such an analysis may help understand the mechanism responsible for the intermittent termination of the downward phase propagation of the easterly regime.

Figure 10 shows the time series for three years of the low-pass filtered zonal wind at selected pressure levels in the lower stratosphere at San Cristóbal (thick lines) and Singapore (thin lines). The time evolution of the QBO zonal wind can be seen to take different shapes in each pressure level. At 15.8 hPa, the westerly acceleration takes almost 300 days from the onset around Day -100 (late October 1991) to the mature westerly phase on Day 200 (July 1992). On the other hand, the easterly acceleration took scarcely 100 days in 1993. The time lag between pressure levels 15.8 and 63.1 hPa is about 400 days for the onset of the westerly acceleration, while it is less than 100 days for that of the easterlies in 1993. It is interesting to see that the easterly acceleration in 1991 is interrupted almost simultaneously in the middle and lower stratosphere coincident with the eruption of Mt. Pinatubo on Day -200 in Fig. 10. It took about eight months for the easterly acceleration to resume its propagation in the lower stratosphere.

Even under such perturbed conditions, the agreement of the QBO component between the two stations is remarkable. However, close inspection may reveal slight differences. On the 25.1 hPa surface, the initiation of the westerly acceleration (Day 100 to 150) may have taken place earlier at San Cristóbal than at Singa-

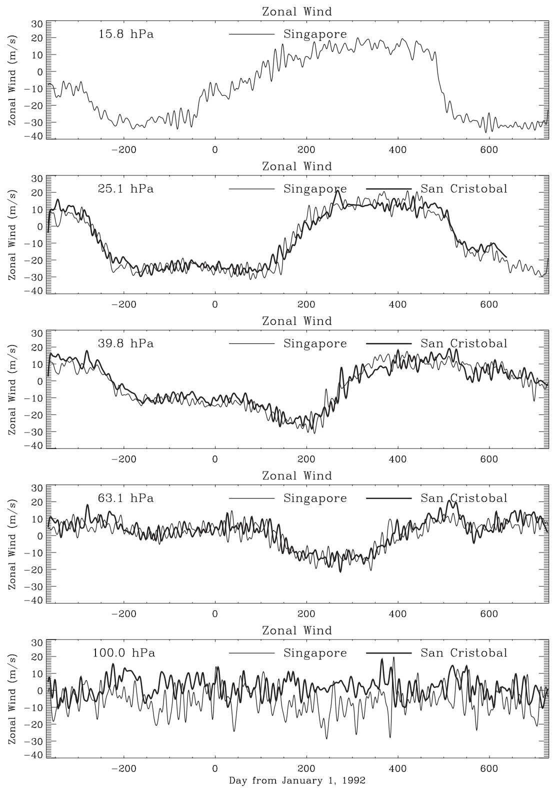

Fig. 10. Time series for three years 1991, 1992, and 1993 of low-pass filtered zonal wind speed at selected pressure levels equally spaced in log pressure. Thick lines are those at San Cristóbal and thin ones are those at Singapore. Not enough data are available on 15.8 hPa surface in San Cristóbal.

pore by about 30 days. At 39.8 hPa, the westerly amplitude may be larger at Singapore than at San Cristóbal from December 1992 to January 1993 (Day 330 to 380). It is also interesting to see correspondence between the 15-day wave activities and the westerly acceleration associated with the QBO. As was pointed out by Shiotani and Horinouchi (1993), the onset of the westerly acceleration is marked by the appearance of the perturbation of the 15-day waves, and that there found little activity of such waves during the easterly acceleration phase. It is also interesting to note that the 15-day component is, in most cases, out-of-phase between the two stations.

4. Discussion

4.1 Interannual variations in tropopause properties

The thermal response of tropospheric air to the tropical ENSO forcing has both zonally uniform (Horrel and Wallace 1981) and asymmetric components. The latter is characterized by the north-south oriented dumbbell pattern located in the central Pacific with its sign reversed in the lower stratosphere (Yulaeva and Wallace 1994). The dumbbell pattern appears as a twin with the opposite polarity in the western and the central Pacific (Randel et al. 2000; Zhou et al. 2001). The zonal gradient of the tropopause potential temperature is known to be reversed corresponding to the sign of SOI (Gage and Reid 1987). The ozone in the lower stratosphere also shows variations in response to ENSO in two characteristic forms (Shiotani and Hasebe 1994): The one is the zonally uniform changes that exhibit a decreasing tendency at the time of El Niño. The other is the zonal seesaw oscillation with the nodal longitude located around the date line. This seesaw pattern corresponds to negative (positive) deviations in the eastern (western) Pacific at the time of El Niño. These two features are interpreted as the advection effect and the tropopause effect, respectively (Hasebe 1993). The advection effect in ENSO is associated with the dynamical forcing by the zonally uniform tropospheric warming. Low temperature anomalies, maintained by adiabatic ascent forced from below, is subject to diabatic heating and drive gradual upward motion in the lowest portion of the stratosphere. The tropopause effect, which appears as an east-west seesaw pattern, is due to the altitude perturbation of the tropopause caused by the local temperature anomaly near the tropopause. The magnitude of the height fluctuations estimated from the ozone variations is on the order of 100 m for the ENSO related phenomenon (Hasebe 1993).

As was shown in the previous section, however, the major components of the interannual variations of the tropopause at San Cristóbal and Singapore are much larger than this estimate and are not directly related to the SOI. In addition, they are synchronized between the east and west Pacific. Possible explanation will be the modulation of the strength of the mean meridional circulation driven by the wave forcing in the extratropics (Yulaeva et al. 1994). How the extratropical pumping could be modulated by the QBO and ENSO is not fully understood. The statistical evidences so far recognized include those in which the Northern polar stratosphere is colder when the QBO in equatorial zonal wind is westerly than in easterly (Holton and Tan 1980, 1982). It is pointed out that this relationship should be modified considering the phase of the solar activity (Labitzke and van Loon 1988; Naito and Hirota 1997). The strength of the residual circulation is also modified associated with the ENSO (Hasebe 1984). As the time scales of the QBO and ENSO are neither fixed nor mutually related as in a multiple, it will be hard to expect some simple relationship between the properties of tropical CPT and SOI.

The idea that the climatological features of the CPT is influenced by some factors other than (or in addition to) the local SST, seems to be consistent with the following notions. First, the potential temperature of the tropopause altitude is appreciably higher than the equivalent potential temperature just above sea level (Reid and Gage 1981; Hasebe 1993). Second, the profile of the correlation coefficient between the air temperature and SST reverses sign from positive to negative well below the local LRT (Reid et al. 1989). If local convection is the prevailing factor to determine the altitude of tropopause, it is natural to expect that the potential temperature of the tropopause is close to the equivalent potential temperature below, and that the correlation coefficient mentioned above remains positive up around the tropopause level. These evidences are consistent with the idea of the TTL.

The lower-stratospheric temperature observed from satellite has a clear zonal wave number 1 structure indicating that the tropopause over the western Pacific is colder than that in the eastern Pacific (Shiotani 1992). Monthly mean Outgoing Longwave Radiation (OLR) data generally show values higher over San Cristóbal (~ 260 W m^{-2}) than over Singapore (~ 215 W m^{-2}). However, there found no evidence of colder CPT over Singapore than over San Cristóbal. This is consistent with the recent results by Gettelman and Forster (2002), who showed that the effect of ENSO does not reach CPT but does affect the altitude of the lapse rate minimum in the upper troposphere. For the altitude of the CPT, ENSO effects are not the dominant factor, QBO may interfere (e.g., Zhou et al. 2001), and there is interannual variability in tropical upwelling that we don't understand completely. One of the points worth mentioning here is that these two stations are not located in the center of action in terms of the dumbbell-shaped SST forcing. Recent investigation by Nishida et al. (2000), using the GPS occultation method, shows that the lowest temperature during the period from December 1996 to February 1997 is located around 170°E that is far east from Singapore. The situation may prove to be even more complex as we note that the climatological tropopause is coldest over the western Pacific while it is highest over the western Atlantic (Seidel et al. 2001). Thus, the usefulness of the present results depends on the representativeness of the two stations having been analyzed. According to the morphology of the gravity wave activity deduced from GPS/MET analysis for November–February period in late 1990's by Tsuda et al. (2000), there appears an active region over the Galápagos so that San Cristóbal may not represent the eastern tropical Pacific, although Singapore could be regarded as a representative of the western tropical Pacific. The accumulation of data widely distributed over the whole tropics will stimulate the research similar to the present one in the future.

4.2 Characteristics of waves

Mutual phase relationship between temperature and zonal wind and the lack of corresponding fluctuations in meridional wind suggest that the variations with period of 15 to 20 days observed in the stratosphere are brought about by equatorial Kelvin waves. Actually the features of waves shown in the present analysis would give the numbers such as the angular frequency $\omega = 2\pi/(18\ \text{days}) \sim 4 \times 10^{-6}\ \text{s}^{-1}$, and the vertical wavenumber $m = 2\pi/(-6\ \text{km}) \sim -1 \times 10^{-3}\ \text{m}^{-1}$. From the observed temperature profiles, we can estimate the Brunt-Väisälä frequency $N = 2.6 \times 10^{-2}\ \text{s}^{-1}$ in the lower stratosphere during Day 110 to 160. The zonal mean zonal wind $\bar{u}$ estimated from ECMWF analysis is about 1 m s^{-1} on 70 hPa. Substituting these values into the dispersion relationship for Kelvin waves, $\omega - k\bar{u} = -Nk/m$ (Andrews et al. 1987), we have the estimate of the zonal wavenumber $k \sim 1.6 \times 10^{-7}\ \mathrm{m}^{-1} = 2\pi/(40000\ \mathrm{km})$, which is consistent with the observational evidence of the out-of-phase relationship between San Cristóbal and Singapore. These parameters would give an estimate of the vertical group velocity such as $\partial\omega/\partial m = Nk/m^2 = 4 \times 10^{-3}\ \mathrm{m\ s}^{-1}$, in a good agreement with one of the ascending velocities of the wavepacket estimated in section *3.3*.

Shiotani and Horinouchi (1993) suggested those waves with typical time scale of 5 days found in the radiosonde data at Singapore as mixed Rossby-gravity waves, since there have been no corresponding variations in zonal wind. The results of the 5-day waves in the present investigation show similar magnitude of variations in meridional and zonal wind components at both San Cristóbal and Singapore. As these stations are located almost on the equator where mixed Rossby-gravity waves possess theoretically no zonal wind component, such an isotropy in the 5-day waves makes us hesitant to regard them as being brought about by mixed Rossby-gravity waves.

It is a surprise that the wave amplitudes are much larger in San Cristóbal than in Singapore, since the tropospheric convection must be more intense in the western than in the eastern tropical Pacific. A possible interpretation is that the altitude of the cloud top, where waves are supposed to be generated by the convective system, is higher in Singapore than in San Cristóbal. Thus, the waves in Singapore are restricted in the upper troposphere, while in San Cristóbal they are frequently observed even in the middle troposphere. Actually, the phase angle often suggests the upward energy propagation in the upper troposphere while it is downward in the lower troposphere, which implies the energy source in the middle troposphere. It will be interesting to see if such waves are generated in the ITCZ region located to the north or in the Andes/Amazon region to the east.

5. Concluding remarks

Statistical properties of the lapse rate tropopause (LRT) and the cold point tropopause (CPT) at San Cristóbal, Galápagos derived from radiosonde data are examined for the first time by comparing them with those at Singapore. The well known behavior of the seasonal variations is confirmed at both stations. It is found that the interannual variations of LRT and CPT features are not directly related to the spatial and temporal variations of the sea surface temperature associated with El Niño. Some other sources such as the modulation of extratropical pumping should be sought to understand the interannual variation of the tropical tropopause properties. The east-west contrast of the tropopause characteristics along the Pacific is not detected between San Cristóbal and Singapore. Recent data from GPS occultation method suggest that Singapore may not properly represent characteristic features of the western tropical Pacific. Accumulation of data in the central and the eastern Pacific is also required.

The daily sequences of temperature and wind profiles exhibit features specific for the vertical wave propagation. Typical time scales are located around 15 day and 5 day periods. The former are interpreted as equatorial Kelvin waves, while the latter would consist mostly of gravity waves. The wave activity in the troposphere is more pronounced over San Cristóbal than in Singapore. It could be interpreted as the difference in the altitude of wave generation associated with the convection. It will be interesting to see if such an interpretation could be valid by looking at the correspondence of such wave generation procedure with cloud activities.

The time evolution and the magnitude of variation in the quasi-biennial oscillation in zonal wind are compared at the two stations. The similarity of the features is high even during the period when the equatorial stratosphere is disturbed by the eruption of Mt. Pinatubo, although some differences in the onset of the wind regime and the strength of mean wind could be recognized.

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