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Annual, Quasi-Biennial, and El Niño-Southern Oscillation (ENSO) Time-Scale Variations in Equatorial Total Ozone

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Equatorial total ozone variations with time scales of annual, quasi-biennial, and about 4-year periodicities are described by paying attention to their longitudinal structure. Analyses are made for 11 years from 1979 to 1989, using the global total ozone data derived from the total ozone mapping spectrometer on board the Nimbus 7 satellite. Over the equator an annual cycle in total ozone is conspicuous. Zonal mean values are maximum around September and minimum around January. The longitudinal structure shows a zonal wavenumber 1 pattern with minimum values around 140°E to the date line all year-round, indicating a close relationship to a region where the convective cloud activity is vigorous. By removing the climatological annual cycle from the original data, there appears the quasi-biennial oscillation in total ozone. This variation is characterized by zonally uniform phase changes and is strongly coupled with the quasi-biennial oscillation of the equatorial zonal wind in the lower stratosphere. Moreover, subtracting zonal mean values from the anomaly data mentioned above, we see an east-west seesaw variation with a nodal longitude around the date line. This east-west variation, having a characteristic time scale of about 4 years, is clearly related to the El Niño and the Southern Oscillation cycle. During El Niño events the longitudinal anomaly field in total ozone is positive in the western Pacific and negative in the eastern Pacific; the anomaly pattern is reversed during anti-El Niño events. Because the active region of convective clouds is located relatively in the eastern Pacific sector during El Niño events, it is suggested that the stronger upwelling and the higher tropopause associated with the convective cloud activity bring about less total ozone.

1. INTRODUCTION

From October 1978 the total ozone mapping spectrometer (TOMS) instrument on board the Nimbus 7 satellite has been in operation to make total ozone measurements using the backscattered ultraviolet technique. (See a review paper of satellite ozone observations by *Miller* [1989].) On the basis of the TOMS data, several findings have been achieved by virtue of its global coverage and homogeneity in space and time. One of the most important observational results is that *Stolarski et al.* [1986] confirmed a decrease of total ozone during the springtime at polar latitudes of the southern hemisphere and showed the phenomenon to be of continental size (a so-called ozone hole). However, less attention has been paid to total ozone variations at equatorial latitudes than at middle and high latitudes where strong longitudinal disturbances due to planetary waves are dominant during winter and spring.

At equatorial latitudes the quasi-biennial oscillation (QBO) in total ozone, which is dynamically coupled with the equatorial zonal wind and temperature QBO in the lower stratosphere, has been reported by several authors using the ground-based observations [e.g., *Angell and Korshover*, 1973; *Hasebe*, 1980] and the zonal mean satellite observations [e.g., *Tolson*, 1981; *Hilsenrath and Schlesinger*, 1981]. Recently, by means of zonal mean statistics based on the TOMS data, *Bowman* [1989] has made a detailed analysis of the global structure of the total ozone QBO. He showed that the interannual variability of total ozone near the equator is dominated by the QBO and that the equatorial total ozone QBO is anticorrelated with middle- and high-latitude ozone variations especially during winter and spring. *Lait et al.* [1989] have made an analysis similar to Bowman's but have focused on the quasi-biennial modulation of the Antarctic ozone depletion; this modulation was first pointed out by *Garcia and Solomon* [1987]. These analyses suggest that the total ozone QBO at middle and high latitudes results from the QBO modulation of the planetary wave activity and the associated ozone transport.

At present, however, there are few good presentations about the longitudinal structure of the total ozone field related with the long-term variations, while in shorter time scales there are some studies by *Gao and Stanford* [1990] on intraseasonal oscillations and *Mote et al.* [1991] on baroclinic waves in the northern hemisphere. *Hasebe* [1983] is the almost only one paying attention to the longitudinal structure of the total ozone QBO, by using the Nimbus 4 BUV and ground-based observations. He showed that the total ozone QBO is characterized by zonally uniform phase changes having larger amplitudes in the western hemisphere. His analysis was, however, based on the only 7 years of data and heavily depended on an interpolation scheme and filtering procedure.

The purpose of this study is to investigate the long-term variations in the equatorial ozone field using the 11-year TOMS data, by paying special attention to the longitudinal structure. After describing the data used in this study in section 2, we will focus on the variations with time scales of annual (section 3), quasi-biennial (section 4), and the El Niño-Southern Oscillation (ENSO) cycle (section 5) periodicities. The summary is in section 6.

2. DATA

The data set used in this study is 11 years (1979–1989) of global total ozone observations from the TOMS instrument. The archival total ozone data we used are called the GRIDTOMS version 5 and were provided by the National Space Science Data Center. The GRIDTOMS data consist of daily

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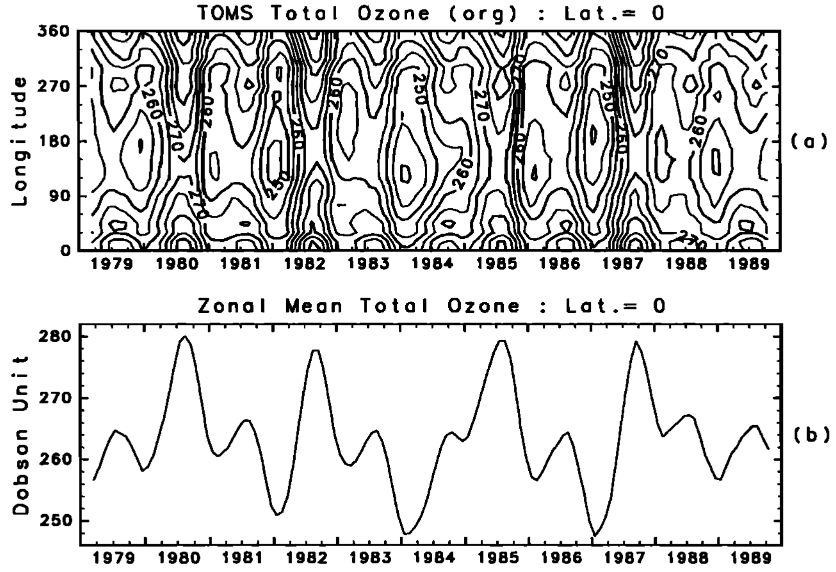

Fig. 1. (*a*) Time-longitude section of the monthly mean total ozone field over the equator (contour interval 5 DU (Dobson units)) and (*b*) curve plot of the zonal mean values (unit, DU).

global total ozone fields on a semiregular latitude-longitude grid. Because the TOMS instrument measures backscattered solar ultraviolet radiation to provide daily total ozone maps, the latitudinal coverage does not extend into the polar night. The latitudinal resolution is 1° and the longitudinal resolution is variable; 5° in longitude for 90° to 70° latitudes, 2.5° for 70° to 50°, and 1.25° for 50° to the equator. Details of the TOMS data are described by *Bowman and Krueger* [1985] and *Bowman* [1989].

To see the large-scale features and relieve the computational burden, we reduced the size of the data set; the GRIDTOMS fields were area averaged onto a 5° × 5° grid, then Fourier transformed to provide a zonal mean and coefficients for 12 longitudinal waves. As a decrease trend of total ozone has been observed especially at high latitudes of the southern hemisphere [e.g., *Farman et al.*, 1985; *Stolarski et al.*, 1986], we removed such trend in zonal mean values for each latitude by subtracting a least squares fit on a maximum of the third order. Base values were retained so as to be the origin on January 1, 1983.

Using this daily 11-year data set, we calculated the climatological annual cycle by averaging the 11 years of data for each calendar day. The resulting time series was then smoothed by applying a 15-day running mean. Moreover, we calculated the daily anomaly by subtracting the annual cycle defined above from the original daily data. In order to see the long-term variation we also calculated monthly mean values from the original and anomaly daily data.

To make further investigations of the climatological temperature field in the lower stratosphere, we used the NOAA-stratospheric sounding unit (SSU) data provided by the British Meteorological Office for the 10-year period from 1980 to 1989. The SSU data give geopotential heights for the following 11 constant pressure levels: 850, 500, 300, 200, 100, 50, 20, 10, 5, 2, and 1 mbar. As for the data processing, we followed a similar procedure to that for the TOMS data, except that the Fourier transform along latitude circles was done up to six longitudinal waves. The SSU data below 50 mbar are essentially the same as the tropospheric global data provided by the U.S. National Meteorological Center (NMC). Then, we found that the SSU data are not so homogeneous in time as the TOMS data, probably because the NMC analysis scheme was changed several times during this period. Therefore we judged that the use of the SSU data is not appropriate to discuss the interannual variation but the climatological annual cycle.

As a reference of the equatorial wind field, monthly mean zonal winds at Singapore (104°E, 1°N) were calculated from the daily radiosonde data. The wind data are available on the following six pressure levels: 100, 70, 50, 30, 20, and 10 mbar.

3. ANNUAL VARIATION

Figure 1*a* shows a time-longitude section of the monthly mean total ozone field over the equator; a time series of the zonal mean values is presented below (Figure 1*b*). A 5-month running mean was applied to most figures based on the monthly mean values, with the exception that no filtering was used for Figure 6 and that a 13-month running mean was used for Figure 7. From Figure 1 an annual variation with a zonal wavenumber 1 component is prominent over the equator. Several authors, using satellite-borne data, have made global analyses of the annual variation in total ozone [e.g., *Tolson*, 1981; *Hilsenrath and Schlesinger*, 1981; *Bowman and Krueger*, 1985]. However, they did not pay much attention to the equatorial latitude, because an annual harmonic amplitude of the zonal mean values and a fraction of the variance explained by the annual harmonic are small around the equator in comparison with those at middle and high latitudes [*Bowman and Krueger*, 1985]. The rest of the variance at equatorial latitudes is attributed to much longer time scale variations such as those with a quasi-biennial periodicity, as can be seen even in Figure 1*b*. The longer time scale variations will be described in detail in sections 4 and 5.

The annual variation in total ozone over the equator is fairly repeatable, indicating that means over 11 years should

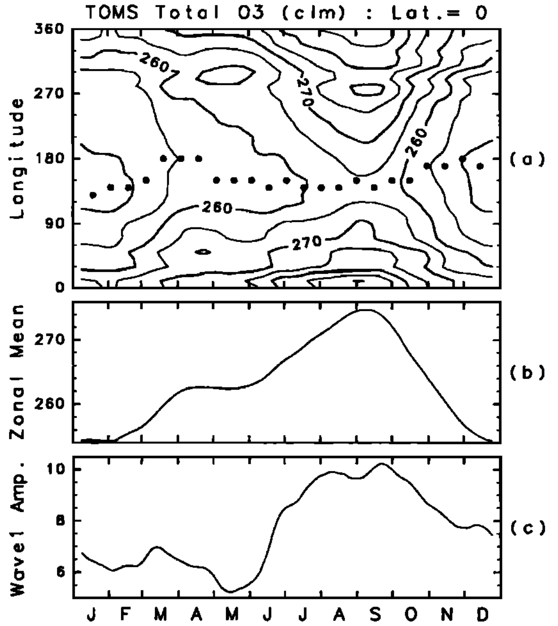

Fig. 2. Climatological annual cycle of the total ozone field over the equator: (*a*) time-longitude section (contour interval 5 DU; longitudinal minima are dotted for every 15 days); curve plots of (*b*) the zonal mean values and (*c*) the wave 1 amplitudes (unit, DU).

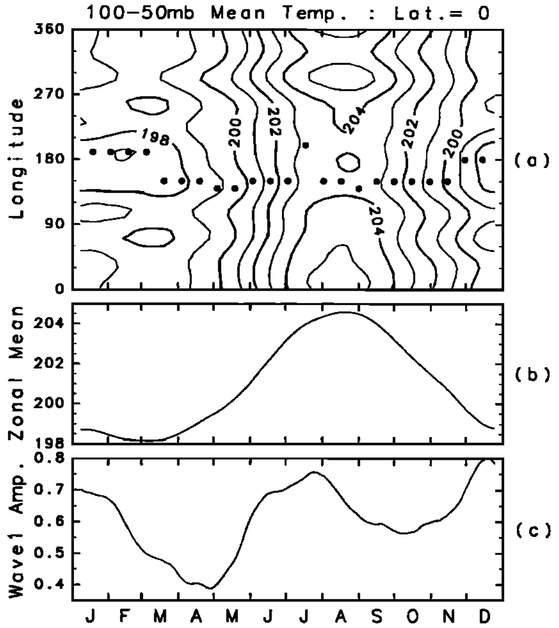

Fig. 3. Climatological annual cycle of the 100- to 50-mbar layer mean temperature field over the equator: (*a*) time-longitude section (contour interval 1 K; longitudinal minima are dotted for every 15 days); curve plots of (*b*) the zonal mean values and (*c*) the wave 1 amplitudes (unit, K).

provide a useful estimate of the climatology. By means of the climatological daily data, which were made by averaging the 11 years of daily data for each calendar day, several aspects of the annual cycle in equatorial total ozone are shown in Figures 2*a*, the longitudinal structure, 2*b*, the zonal mean values, and 2*c*, the wave 1 amplitudes. In the following a 15-day running mean was applied to all figures based on the daily values. The climatological features of the annual cycle are summarized as follows:

1. Zonal mean values are maximum around September and minimum around January.

2. All year-round, the zonal wavenumber 1 pattern is persistent with minimum values around 140°E to the date line.

3. The wave 1 amplitudes are maximum around September.

Concerning the temporal variation in zonal mean values, there is a secondary maximum in April and a secondary minimum in May, suggesting that a slight semiannual component is superimposed on the annual cycle. The location of minimum total ozone around the western Pacific is suggestive of the vigorous convective activity there. We will discuss interpretations of these features after presenting Figure 3.

To provide a background for a better understanding of the annual cycle in the total ozone field, we next investigate the temperature field in the lower stratosphere. Figure 3 shows similar figures to Figure 2 but for the climatological annual cycle of the 100- to 50-mbar layer mean temperature field estimated from the SSU thickness data of 10 years, 1980–1989. The climatological features of the annual cycle in the lower stratosphere temperature field are compared with Figure 2 and summarized as follows:

1. Zonal mean values are maximum around August and minimum around March.

2. The zonal wavenumber one pattern is persistent with minimum values around 140°E to the date line.

3. The wave 1 amplitudes show a semiannual variation with maximum values around July and December.

The annual variation in the lower stratosphere temperature field is basically similar to that in the total ozone field, in the sense that cold (warm) temperature in space and time almost corresponds to low (high) total ozone. There is no significant relationship in the seasonal march of the wave 1 amplitudes between the two fields; however, the semiannual variation of the temperature-wave 1 amplitudes having maximum values around solstitial seasons may be understood as cross-equatorial propagation of stationary planetary waves in the winter hemisphere. At the higher layer (50–20 mbar), where the number density of ozone has largest values, less relation can be seen between the total ozone field and the layer mean temperature field (the figure is not shown).

Making use of rawinsonde station data, *Newell et al.* [1969] and *Reed and Vlcek* [1969] found in the temperature field of the equatorial lower stratosphere that there is a distinct annual cycle with an amplitude about 4 K and a phase with a maximum in August; these results are consistent with ours using the recent global data set. They attributed this variation to an annual modulation of the rising motion in the tropical Hadley cell and consequent changes in the adiabatic cooling, though the source of the modulation was not known. Concerning the longitudinal structure in the lower stratosphere temperature field, the almost stationary cold region in Figure 3*a* is related to a so-called "stratospheric fountain" over the tropical western Pacific at 100 mbar, which was found by *Newell and Gould-Stewart* [1981] using a huge amount of station data.

The temperature variation in the lower stratosphere is closely coupled with the height and temperature variation of the tropopause [*Cole*, 1975; *Reid and Gage*, 1981]. Using

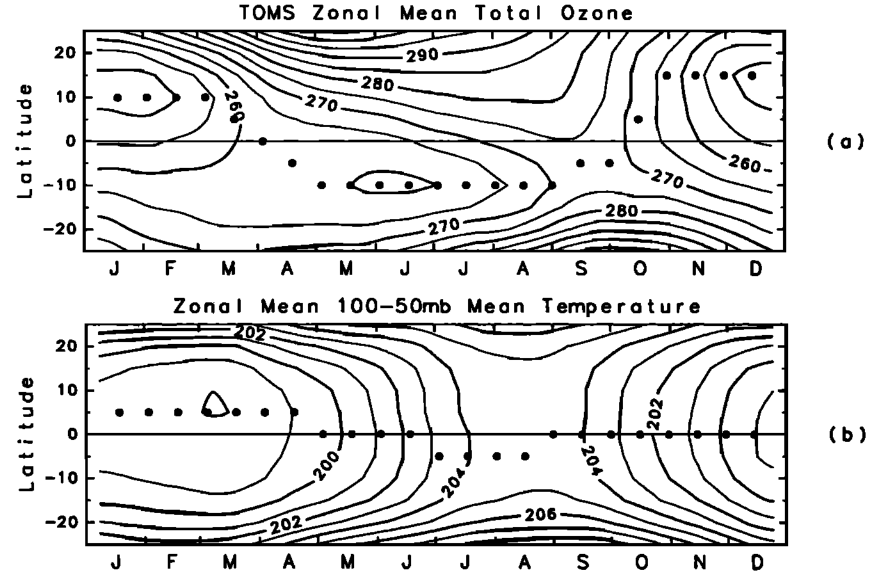

Fig. 4. Climatological time-latitude sections at equatorial latitudes (25°S–25°N) of (*a*) the zonal mean total ozone (contour interval 5 DU) and (*b*) the zonal mean 100- to 50-mbar layer mean temperature (contour interval 1 K). Latitudinal minima are dotted for every 15 days.

routine rawinsonde data at a number of tropical Pacific stations, *Reid and Gage* [1981] found that the tropical Pacific tropopause is about 1–2 km higher and 5 K colder during the northern hemisphere winter than during the northern hemisphere summer. On the basis of a model calculation, which demonstrates an annual variation in equatorial sea surface temperature (SST) with maximum values around April and minimum values around August, they proposed the following scenario: The higher SSTs at equatorial latitudes during the northern hemisphere winter provide much moisture and activate convective cloud system; then, the adiabatic cooling in the lower stratosphere associated with the Hadley circulation can produce the lower temperature and higher altitude of the tropopause.

If we accept the observation by *Reid and Gage* [1981] showing that the equatorial tropopause is higher during the northern hemisphere winter than during the northern hemisphere summer, though the mechanism of the tropopause height change is still not fully verified, we can infer that the change in tropopause height should have an influence on total ozone in the following way: The higher tropopause brings about the erosion of the ozone layer in the lower stratosphere; then, this will give less total ozone, if we assume that ozone mixing ratios below the tropopause, which is much less than the stratospheric ones, could be kept constant by such processes as prompt horizontal and vertical mixing. The higher tropopause also explains the lower temperature in the lower stratosphere. Moreover, this mechanism can be applied to the longitudinal distribution of total ozone; because the tropopause is probably higher and colder over the western Pacific where there is vigorous convective activity due to the higher SSTs, it will give less total ozone, as seen in Figure 2*a*. As will be inferred from Figure 4, however, the temporal variation in SST does not seem to have a direct influence on the annual cycle in the tropopause height changes.

To verify latitudinal extension of the annual cycle in the total ozone and temperature fields, time-latitude sections of their zonal mean values around the equator (25°S–25°N) are presented in Figure 4. The annual variation for both the ozone and the temperature fields are almost in phase around the equator. In addition, in the total ozone field we see a swing of minimum values between 15°N and 10°S of the winter hemisphere and strong seasonality with maximum values at subtropical latitudes during the springtime for each hemisphere; these maximum values, known as the so-called spring maximum, are due to stronger planetary wave activity at middle and high latitudes during the winter and spring seasons than during the summer season.

The swing of minimum total ozone is not simply due to changes in upward motion or tropopause height associated with convective activity resulting from higher SSTs, because the convective activity should be much more vigorous in the summer hemisphere than in the winter hemisphere. On the basis of the zonal mean climatology of the outgoing long-wave radiation (OLR), smaller values of which mean larger amount of high clouds, N. Nishi (personal communication, 1991) showed a swing of minimum values of the OLR between 10°N and 10°S of the summer hemisphere; this swing of the OLR is related to the similar SST variations with high values in the summer hemisphere. Thus the SST variation and the associated cloud activity do not have direct effects on the annual cycle in the temperature field nor the tropopause height.

It is suggested that the swing may be due to the photochemical effect related to the O_2 photolysis rate varying with the solar zenith angle, because the times of minimum values almost correspond to the winter solstice. *Perliski et al.* [1989] have examined annual and semiannual variations of stratospheric ozone using the ozone mixing ratio data derived from the solar backscatter ultraviolet (SBUV) instrument and found strong semiannual variability in the equatorial stratosphere. Using a two-dimensional photochemical model, they showed that the semiannual variability in the equatorial middle and lower stratosphere is largely con-

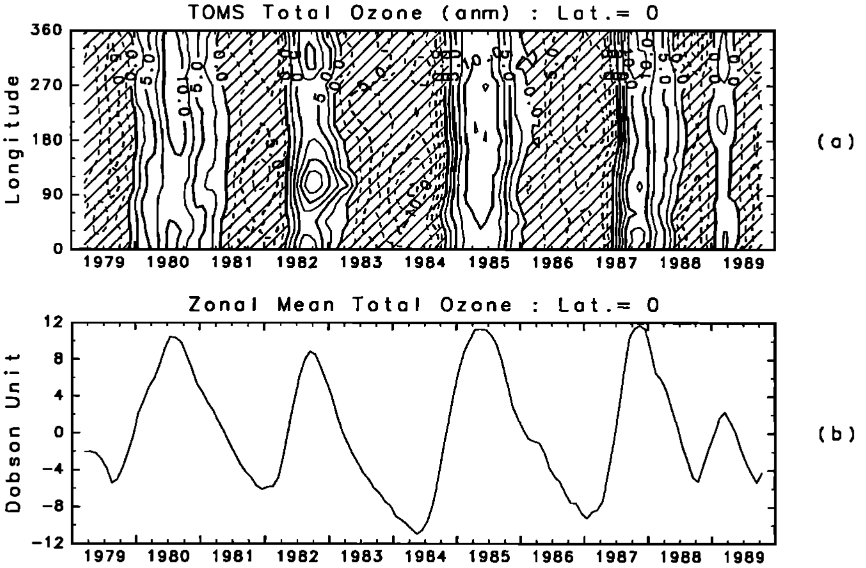

Fig. 5. (*a*) Time-longitude section of the monthly mean anomaly field of total ozone over the equator (contour interval 2.5 DU, negative values are hatched) and (*b*) curve plot of the zonal mean values (unit, DU).

trolled by the production of odd oxygen (O and O_3) by photolysis of molecular oxygen.

The annual variation of the lower stratosphere temperature field seems to be attributed to an annual modulation of the upward motion in the tropical Hadley cell, as was postulated by *Newell et al.* [1969] and *Reed and Vlcek* [1969]. Using the eddy momentum and heat flux data taken from Oort's 15-year climatology, *Holton* [1990] estimated seasonal mean upward mass fluxes from the troposphere to the stratosphere in the tropics, by applying a principle of "downward control" proposed by *Haynes and McIntyre* [1987] and *Haynes et al.* [1991]. He found that the upward flux is a maximum during the northern hemisphere winter and a minimum during the northern hemisphere summer, which is consistent with the stronger planetary eddy forcing in the northern hemisphere than in the southern hemisphere. The stronger upward flux should be coupled with lower temperature associated with change in the adiabatic cooling in the equatorial lower stratosphere. Moreover, this annual variation in the strength of the cross-tropopause mass flux due to the greater stratospheric wave activity in the northern hemisphere winter may explain a part of the annual variation in total ozone through its advection effect; also, the seasonal variation of the cross-tropopause mass flux may be the main cause of the tropopause height changes.

Thus the total ozone variation over the equator shows a primarily annual cycle affected by the tropopause height change, which may be associated with the upward mass flux, and a secondary semiannual cycle due to the swing of the minimum values resulting from the photochemical effect.

4. QUASI-BIENNIAL OSCILLATION (QBO)

Though the total ozone variation has a clear annual component over the equator, the annual cycle is modulated by much longer time scale variations, as can be seen in Figure 1*b*. Figure 5*a* shows a time-longitude section of the monthly mean anomaly field; the anomaly field was constructed by subtracting the climatological (11-year mean) annual cycle from the original data. A time series of the zonal mean values of the anomaly field is also presented (Figure 5*b*). There is a clear signal of the QBO in total ozone having a zonally uniform phase structure. The amplitude of the QBO variation is about 10 dobson units (DU), which is a compatible order of the annual variation (Figure 2*b*); this is consistent with the earlier result by *Hilsenrath and Schlesinger* [1981] using the 7-year Nimbus 4 BUV data.

Because of its strong zonality there have been many studies of the equatorial total ozone QBO on the basis of station data and/or zonal mean satellite data [e.g., *Angell and Korshover*, 1973; *Oltmans and London*, 1982; *Hilsenrath and Schlesinger*, 1981; *Bowman*, 1989]. Given by *Hasebe* [1983] is the almost only result concerning the longitudinal structure of the total ozone QBO, using band-pass filtered data from the Nimbus 4 BUV and ground-based observations for 7 years, 1970–1977. He showed that the total ozone QBO is characterized by zonally uniform phase changes and that the QBO amplitude is larger in the western hemisphere. With respect to the QBO amplitude, Hasebe's result is not always the case for ours, probably because in our analysis there still exist contributions from much longer time scale variations, such as those that will be described in section 5.

Since a number of authors have already made analyses of the zonal mean total ozone QBO, we will not make a detailed discussion here; however, we will introduce briefly how the total ozone QBO is related to the dynamical (wind and temperature) QBO, following a discussion by *Plumb and Bell* [1982]: As for atmospheric phenomena having a long time scale like the QBO, the thermal wind balance holds even at equatorial latitudes; in the westerly (easterly) shear zone there is warm (cold) anomaly. This temperature field is sustained by the vertical motion; in the westerly (easterly) shear zone there is downward (upward) motion. In the lower stratosphere, where photochemical lifetime is longer than advective time scale, downward motion brings ozone-rich air from the above and upward motion brings ozone-poor air from the below. Thus in the westerly (easterly) shear zone the total ozone must increase (decrease).

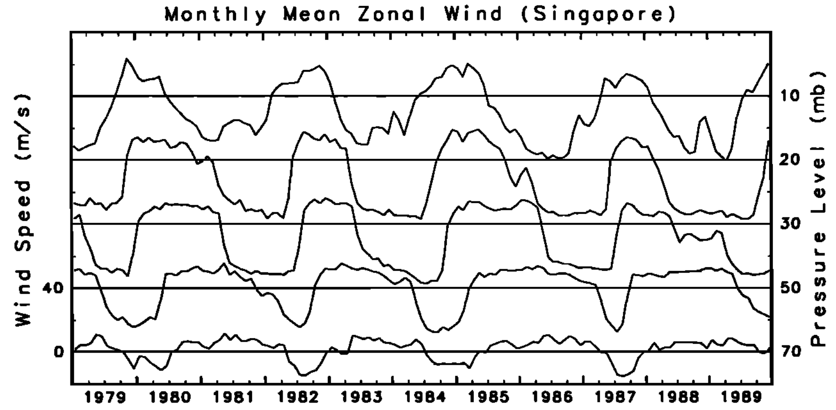

Fig. 6. Curve plots of the monthly mean zonal wind at Singapore for pressure levels 70, 50, 30, 20, and 10 mbar. Vertical axis is scaled 40 m s^{-1} by two horizontal lines.

This relation is clearly seen in Figure 5*b* of the total ozone QBO and Figure 6 of the zonal wind QBO; Figure 6 shows line plots of the monthly mean zonal wind at Singapore. In addition, it should be noted that there is a short break of the QBO cycle in the total ozone variation during late 1988 to early 1989. The zonal wind at Singapore also shows a weakening of easterlies at 10 mbar and very weak easterlies at 30 mbar. Though, at present, we do not have any detailed description of this break in other dynamical fields, it should be interesting to investigate the peculiar behavior of the QBO during this period.

5. EL NIÑO-SOUTHERN OSCILLATION (ENSO) CYCLE

Subtracting zonal mean values from Figure 5*a* to see variations in longitudinal anomaly, there appears an east-west seesaw pattern with a nodal longitude around the date line (Figure 7*a*). This east-west variation has a characteristic time scale of about 4 years and is clearly related to the ENSO cycle. The Southern Oscillation is one of the prominent climate anomalies in the equatorial atmosphere, showing a standing variation of pressure anomalies between the Indian Ocean and the Pacific Ocean in an opposite sense. This variation is mutually coupled with the SST variation in the eastern Pacific Ocean, particularly with warm SST anomaly events, so-called El Niño events. As an index representing this fluctuation, we usually use the Southern Oscillation index (SOI) which is a measure of the pressure gradient between Tahiti (18°S, 150°W) and Darwin (12°S, 131°E). In Figure 7*b*, plotted in solid curve is the SOI adopted from the monthly report on the climate system by the *Japan Meteorological Agency* (*JMA*) [1991] and plotted in dashed curve is the east-west gradient of the total ozone anomaly field defined by the difference between averages of the western Pacific region (60°–165°E) and the eastern Pacific region (75°–180°W). During the El Niño events (1982–1983, 1986–1987), when the SOI has large negative values, there are positive anomalies in the western Pacific and negative anomalies in the eastern Pacific, resulting in a positive east-west gradient of the total ozone anomaly field; the anomaly pattern, thus the gradient, is reversed during the anti-El Niño events.

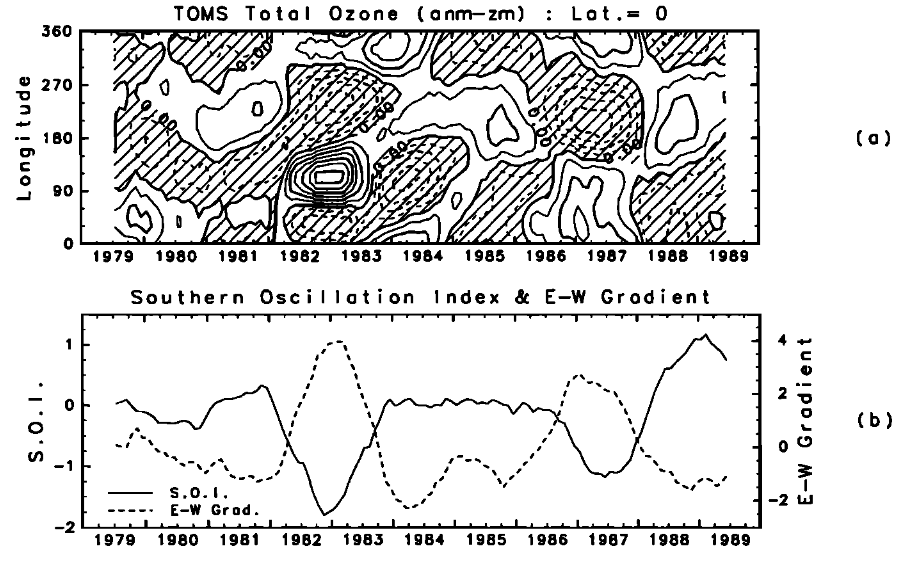

Fig. 7. (*a*) Time-longitude section of the monthly mean anomaly field of total ozone over the equator (zonal mean values are subtracted, contour interval 1 DU, negative values are hatched) and (*b*) curve plots of the Southern Oscillation index (SOI) (solid curve) and the east-west gradient of the total ozone anomaly field (dashed curve). For definition, see text.

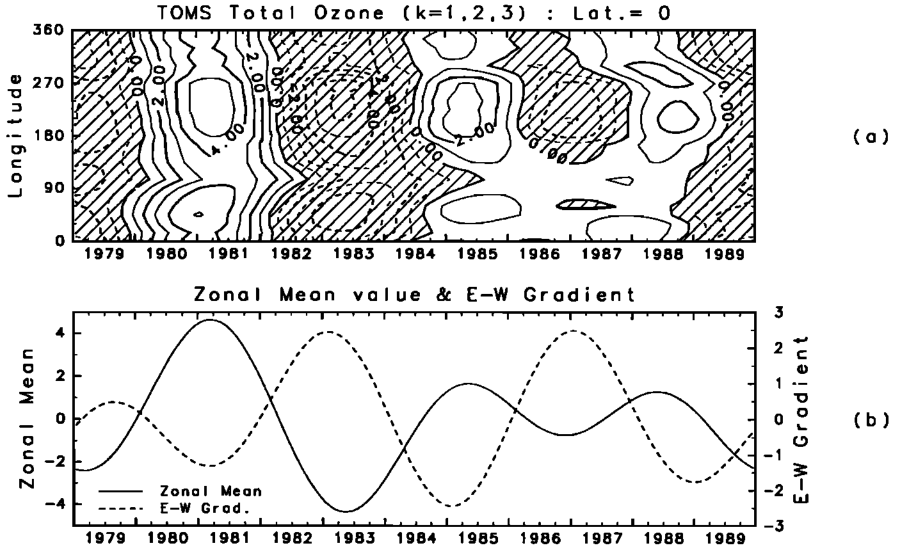

Fig. 8. (*a*) Time-longitude section of the filtered monthly mean total ozone field over the equator (see text for the filtering procedure; contour interval 1 DU, negative values are hatched) and (*b*) curve plots of the zonal mean values (solid curve) and the east-west gradient of the filtered field (dashed curve).

Because the SSTs in the eastern Pacific are higher during El Niño events than during anti-El Niño events, an active region of convective clouds moves relatively eastward; this must bring about a change in longitudinal structure of the tropopause height. According to *Gage and Reid* [1987] the tropopause potential temperature during El Niño events is warm at Koror (7°N, 134°E), as compared to Majuro (7°N, 171°E), and thus the difference in the tropopause potential temperature and also in the tropopause height between the two stations is correlated well with the SOI. These tropical tropopause properties related to the ENSO events support our results; the eastward movement of active convective region during the ENSO events should be accompanied with relatively higher tropopause in the eastern Pacific so as to reduce the total amount of ozone, as followed by the same mechanism explained in section 3.

Because the TOMS instrument cannot see through clouds, we have to be careful with the possibility of systematic errors in the TOMS retrievals as a result of cloud contamination. Very recently, using a simple mechanistic relationship based on the observed SST variation, *Hasebe* [1992] has successfully derived such ENSO-related variation in total ozone with an east-west seesaw pattern, as seen in Figure 7*a*; his result convinces us that the variation seen in Figure 7 should not be simply due to the systematic error in the TOMS retrievals.

This variation with a time scale of about 4 years is reexamined, including zonal mean values. The data period of 11 years is not long enough to apply a numerical filtering procedure for capturing low-frequency variations such as those having time scales of several years. To see gross features of the ENSO time-scale variation, we used Fourier transform for time series of each longitude grid point and made a composite time-longitude section from the gravest three wave components (i.e., 11-, 5.5-, and 3.7-year periodicities). Figure 8*a* shows a time-longitude section produced by the procedure mentioned above; in Figure 8*b* the zonal mean value is plotted in solid curve, and the east-west gradient defined as a similar way to Figure 8*b* is plotted in dashed curve. Referring back to a time series of the east-west gradient in Figure 7*b*, it is safely said that the procedure we used in Figure 8 can capture essential features of this ENSO time-scale variation. The variation has almost a zonally uniform phase structure with its delay in the western Pacific region. The zonal mean values and the east-west gradient are in good negative correlation. This zonal oscillation may be understood as an ENSO time-scale modulation of the tropical Hadley cell.

Hasebe [1983] pointed out that there exists a 4-year oscillation (FYO) in total ozone based on the 7-year observations of Nimbus 4 BUV and ground-based network data. As he noticed, the FYO is related to the sea surface temperature in the equatorial eastern Pacific. Indeed, he looked at the ENSO time-scale variation similar to our results, though his analysis spanned only 7 years and he basically noticed the variation in zonal component, but not the longitudinal seesaw pattern. Thus it can be summarized that the total ozone variation associated with the ENSO cycle consists of two major components from the east-west seesaw variation and the zonally uniform phase variation. The seesaw variation seems to be related to the longitudinal changes in the tropopause height associated with convective cloud activity due to the higher SSTs, while the zonal variation may be related to the modulation of the tropical Hadley cell.

6. SUMMARY

Using the 11-year TOMS data, we have found the following dominant long-term variations in the equatorial total ozone field, by paying special attention to the longitudinal structure.

Annual cycle. This variation has a longitudinal structure with a zonal wavenumber 1 pattern; the zonal mean values are maximum around September and minimum around January. The wave 1 pattern is persistent all over the year with minimum values around 140°E to the date line. There is a synchronous variation in the lower stratosphere temperature, which is related to the variation in tropopause height [*Reid and Gage*, 1981]; when the lower stratosphere temperature is lower, the tropopause is higher, then the erosion of the lower stratosphere ozone layer should give less total ozone. Thus the annual variation in total ozone could be mainly attributed to that in tropopause height, although a mechanism of the tropopause height variation is not yet clear. The wave 1 structure can also be regarded as the tropopause height variation in longitudinal direction; this longitudinal structure should be produced by the active convective cloud system in the western Pacific, which brings about the higher tropopause there.

QBO cycle. This variation shows zonally uniform phase changes and is clearly coupled with the equatorial zonal wind QBO in the lower stratosphere. The total ozone QBO can be easily attributed to the dynamical QBO through the variation of the vertical motion [*Plumb and Bell*, 1982].

ENSO cycle. In the longitudinal anomaly field there is an east-west seesaw variation with a nodal longitude around the date line, having a characteristic time scale of about 4 years. During the El Niño events there are positive anomalies in the western Pacific and negative anomalies in the eastern Pacific; the anomaly pattern is reversed during the anti-El Niño events. The variation in zonal mean values also has the ENSO time scale; the zonal mean values are less during the El Niño events than during the anti-El Niño events. The east-west seesaw pattern must be due to the longitudinal variation in the tropopause height associated with the convective cloud system in the ENSO cycle; the zonal variation may be related to the modulation of the tropical Hadley cell.

Very recently, *Hasebe* [1992] has tried to understand quantitatively these long-term variations by using a simple mechanistic relationship, taking into account the two dynamical processes: the advection effect and the tropopause effect. The advection effect is caused by the vertical advection by diabatically driven mean meridional circulation. The tropopause effect is caused by the change in altitude of the tropopause. On the basis of the observed zonal wind and SST he has successfully derived long-term variations similar to those in this study. In his terminology the annual and ENSO cycles are understood as mainly the tropopause effect, and the QBO cycle is understood as the advection effect.

In the course of this study it is found that the dynamical properties in the tropical lower stratosphere including the tropopause are very important to understand the total ozone variations. In particular, as a next step of this study, it would be interesting to investigate the nature of the tropopause and the annual variation of the lower stratosphere temperature. The scope of the investigation should be enlarged not only in the tropical latitudes but also in the middle and high latitudes, because the stronger planetary wave forcing in the winter hemisphere could modulate the upward motion in the tropical Hadley cell.

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REFERENCES

Angell, J. K., and J. Korshover, Quasi-biennial and long-term fluctuations in total ozone, *Mon. Weather Rev.*, *101*, 426–443, 1973.

Bowman, K. P., Global pattern of the quasi-biennial oscillation in total ozone, *J. Atmos. Sci.*, *46*, 3328–3343, 1989.

Bowman, K. P., and A. J. Krueger, A global climatology of total ozone from the Nimbus 7 total ozone mapping spectrometer, *J. Geophys. Res.*, *90*, 7967–7976, 1985.

Cole, H. P., An investigation of a possible relationship between the height of the low-latitude tropopause and sun spot number, *J. Atmos. Sci.*, *32*, 998–1001, 1975.

Farman, J. C., B. G. Gardiner, and J. D. Shanklin, Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction, *Nature*, *35*, 207–210, 1985.

Gage, K. S., and G. C. Reid, Longitudinal variations in tropical tropopause in relation to tropical convection and El Niño-Southern Oscillation events, *J. Geophys. Res.*, *92*, 14,197–14,203, 1987.

Gao, X. H., and J. L. Stanford, Low-frequency oscillations in total ozone measurements, *J. Geophys. Res.*, *95*, 13,797–13,806, 1990.

Garcia, R. R., and S. Solomon, A possible relationship between interannual variability in Antarctic ozone and the quasi-biennial oscillation, *Geophys. Res. Lett.*, *14*, 848–851, 1987.

Hasebe, F., A global analysis of the fluctuation of total ozone, II, Non-stationary annual oscillation, quasi-biennial oscillation, and long-term variations in total ozone, *J. Meteorol. Soc. Jpn.*, *58*, 104–117, 1980.

Hasebe, F., Interannual variations of global total ozone revealed from Nimbus 4 BUV and ground-based observations, *J. Geophys. Res.*, *88*, 6819–6834, 1983.

Hasebe, F., Dynamical response of the tropical total ozone to the stratospheric zonal wind and the sea surface temperature changes, *J. Atmos. Sci.*, in press, 1992.

Haynes, P. H., and M. E. McIntyre, On the evolution of vorticity and potential vorticity in the presence of diabatic heating and frictional or other forces, *J. Atmos. Sci.*, *44*, 828–841, 1987.

Haynes, P. H., C. J. Marks, M. E. McIntyre, T. G. Shepherd, and K. P. Shine, On the "downward control" of extratropical diabatic circulations by eddy-induced mean zonal forces, *J. Atmos. Sci.*, *48*, 651–678, 1991.

Hilsenrath, E., and B. M. Schlesinger, Total ozone seasonal and interannual variations derived from the 7-year Nimbus 4 BUV data set, *J. Geophys. Res.*, *86*, 12,087–12,096, 1981.

Holton, J. R., On the global exchange of mass between the stratosphere and troposphere, *J. Atmos. Sci.*, *47*, 392–395, 1990.

Japan Meteorological Agency (JMA), Monthly report on climate system, (in Japanese), *Tech. Note 34*, 71 pp., 1991.

Lait, L. R., M. R. Schoeberl, and P. A. Newman, Quasi-biennial modulation of the Antarctic ozone depletion, *J. Geophys. Res.*, *94*, 11,559–11,571, 1989.

Miller, A. J., A review of satellite observations of atmospheric ozone, *Planet. Space. Sci.*, *37*, 1539–1554, 1989.

Mote, P. W., J. R. Holton, and J. M. Wallace, Variability in total ozone associated with baroclinic waves, *J. Atmos. Sci.*, *48*, 1900–1903, 1991.

Newell, R. E., and S. Gould-Stewart, A stratospheric fountain? *J. Atmos. Sci.*, *38*, 2789–2796, 1981.

Newell, R. E., J. W. Kidson, and D. G. Vincent, Annual and biennial modulations in the tropical Hadley cell circulation, *Nature*, *222*, 76–78, 1969.

Oltmans, S. J., and J. London, The quasi-biennial oscillation in atmospheric ozone, *J. Geophys. Res.*, *87*, 8981–8989, 1982.

Perliski, L. M., S. Solomon, and J. London, On the interpretation of seasonal variations of stratospheric ozone, *Planet. Space. Sci.*, *37*, 1527–1538, 1989.

Plumb, R. A., and R. C. Bell, A model of the quasi-biennial oscillation on an equatorial beta-plane, *Q. J. R. Meteorol. Soc.*, *108*, 335–352, 1982.

Reed, R. J., and C. L. Vlcek, The annual temperature variation in the lower tropical stratosphere, *J. Atmos. Sci.*, *26*, 163–167, 1969.

Reid, G. C., and K. S. Gage, On the annual variation in height of the tropical tropopause, *J. Atmos. Sci.*, *38*, 1928–1938, 1981.

Stolarski, R. S., A. J. Krueger, M. R. Schoeberl, R. D. McPeters, P. A. Newman, and J. C. Alpert, Nimbus 7 SBUV/TOMS measurements of the springtime Antarctic ozone hole, *Nature*, *322*, 808–811, 1986.

Tolson, R. H., Spatial and temporal variations of monthly mean total columnar ozone derived from 7 years of BUV data, *J. Geophys. Res.*, *86*, 7312–7330, 1981.

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