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OBSERVATIONAL EVIDENCE AND DYNAMICAL INTERPRETATION OF THE TOTAL OZONE VARIATIONS IN THE EQUATORIAL REGION

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1 Introduction

The total ozone amount is sensitive to the general circulation changes in the lower stratosphere due to the photochemically inactive nature of ozone there. In the equatorial region, such circulation changes arise from the quasi-biennial oscillation (QBO) of the stratospheric zonal wind and the El Niño/Southern Oscillation (ENSO). In the first half of this study we present observational results of the long-term variations in the equatorial ozone field using the 11-year Total Ozone Mapping Spectrometer (TOMS) data, by paying special attention to the longitudinal structure. In the latter half we try to understand quantitatively these variations by using a simple mechanistic relationship. We hypothesize that the ozone modulating processes are attributable to two dynamical effects, the advection effect and tropopause effect, owing to the strong vertical stratification of ozone existing just above the tropopause. The advection effect comes from the vertical motion which maintains the temperature structure, compensating for the radiative damping. The tropopause effect is associated with the altitude change of the tropopause. The total ozone variations in the tropics is discussed in terms of these two dynamical processes with the aid of mechanistic equations combined with the wind and sea surface temperature (SST) observations. The interactions between tropical and extratropical latitudes are beyond the scope of this study. Photochemical effects are also neglected. Details of this study are given by Shiotani (1992) and Hasebe (1992).

2 Observational Evidence

2.1 Annual Variation

From Fig. 1, showing a time-longitude section of the monthly mean total ozone field, we see that an annual variation with a zonal wavenumber one component is prominent over the equator. 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 the year round, the zonal wavenumber one pattern is persistent with minimum values between 140°E and the date line. (3) The wave 1 amplitudes are maximum around September. The location of minimum total ozone around the western Pacific is suggestive of the vigorous convective activity there.

These features in total ozone are closely related to the temperature field in the lower stratosphere. By using the 100– 50 mb layer mean temperature field estimated from the SSU (stratospheric sounding unit) thickness data for 1980 to 1989 (not shown), the climatological features of the annual cycle in the lower stratosphere temperature field are 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 between 140°E and 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 corresponds approximately to low (high) total ozone.

2.2 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. Fig. 2 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. 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 DU (Dobson unit), which is of comparable order to the annual variation. 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). Thus, we will not make a detailed discussion here.

2.3 ENSO Cycle

Subtracting zonal mean values from Fig. 2 to see variations in longitudinal anomaly, there appears to be an east-west seesaw pattern with a nodal longitude around the date line (Fig. 3 (a)). This east-west variation has a characteristic time-scale of about 4 years, and is clearly related to the El Niño and the Southern Oscillation (ENSO) cycle. The Southern Oscillation is one of the prominent climate anomalies in the equatorial atmosphere, showing

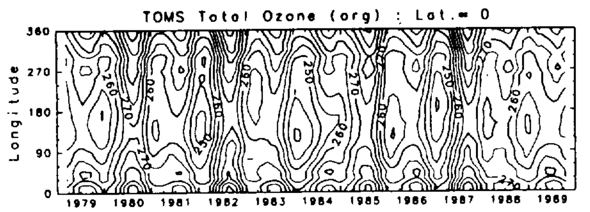

Fig. 1 Time-longitude section of the monthly mean total ozone field over the equator (contour interval 5 DU: Dobson unit); a 5-month running mean was applied.

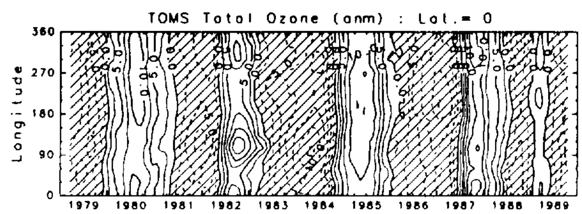

Fig. 2 Time-longitude section of the monthly mean anomaly field of total ozone over the equator (contour interval 2.5 DU, negative values are hatched); a 5-month running mean was applied.

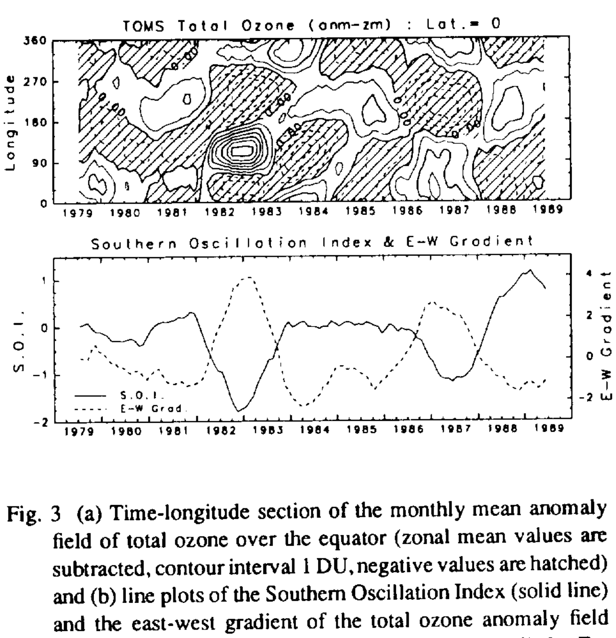

Fig. 3 (a) Time-longitude section of the monthly mean anomaly field of total ozone over the equator (zonal mean values are subtracted, contour interval 1 DU, negative values are hatched) and (b) line plots of the Southern Oscillation Index (solid line) and the east-west gradient of the total ozone anomaly field (dashed line); a 13-month running mean was applied. For definition, see text.

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: the so-called El Niño. As an index representing this fluctuation, we usually use the Southern Oscillation Index (S.O.I.) which is a measure of the pressure gradient between Tahiti (18°S, 150°W) and Darwin (12°S, 131°E). In Fig. 3 (b), the S.O.I. adopted from Monthly Report on Climate System by the Japan Meteorological Agency (1991) is plotted in solid line. Plotted in dashed line 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 (1982-83, 1986- 87) when the S.O.I. has large negative values, there are positive anomalies in the western Pacific and negative anomalies in the eastern Pacific, resulting in positive east-west gradient of the total ozone anomaly field; the anomaly pattern, thus the gradient, is reversed during the anti-El Niño events.

Because the sea surface temperatures 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 S.O.I. These tropical tropopause properties related with 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 mechanism introduced in the following section.

3 Dynamical Interpretation

3.1 Response to zonal wind QBO

The total ozone QBO in the tropics is believed to be driven by vertical ozone advection. On the time scale of the QBO, the geostrophic approximation is valid even quite near the equator. Then the vertical wind shear of the mean zonal wind is proportional to the meridional gradient of the zonal mean temperature as described by the thermal wind equation. This temperature structure is damped radiatively by infra-red cooling. The diabatic circulation driven by this radiative heating is a good approximation to the Lagrangian mean circulation (cf. Plumb and Bell, 1982). Owing to the strong vertical stratification of ozone, the time change of the zonal mean ozone is approximated by the vertical advection of the basic state ozone distribution. Assuming a Gaussian form for the meridional structures of zonal wind and temperature, a mechanistic equation for the total ozone QBO is derived on an equatorial beta-plane. This equation is combined with the zonal wind data provided by Naujokat (1986) to simulate the total ozone QBO. The results are shown together with observations in Fig. 4. We can see some systematic phase difference between the two time series. Our preliminary investigations suggest that the feedback of the ozone QBO to diabatic heating possibly resolves this disagreement.

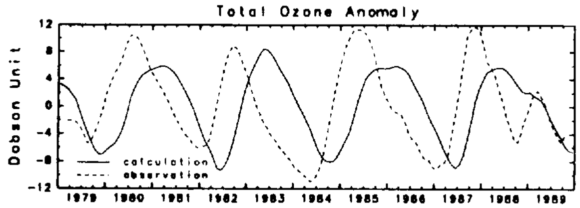

Fig. 4 Line plots of the total ozone QBO over the equator: derived values by using the observed zonal wind are plotted in solid line and zonal mean values in Fig. 2 are plotted in dashed line.

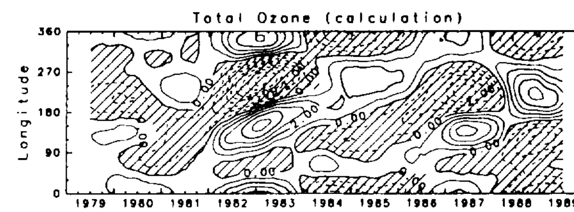

Fig. 5 Time-longitude cross section of the zonal wave component of total ozone fluctuations (contour interval 1 DU) along the equator based on estimation from SST; a 13-month running mean was applied.

3.2 Response to ENSO time-scale SST

In section 2.3 we have revealed an east/west seesaw pattern of equatorial total ozone correlated with the Southern Oscillation Index. This is understood to be a reflection of the tropopause effect of SST variations. High SST's, for example, would give increased evaporation and cumulus convection, lift up the tropopause, and thus reduce the total ozone amount. Tropopause height changes are estimated from the Climate Analysis Center's monthly mean SST by using the equivalent potential temperature in the manner of Reid and Gage (1981). The associated total ozone variations are derived by applying small perturbatins of the tropopause height to the basic state ozone profile. The results are shown in Fig. 5, which is the time-longitude section of the zonal wave component of tropical total ozone. The general agreement between Figs. 3 and 5, especially at the time of El Niño, indicates that the zonal wave component of equatorial total ozone on the ENSO time scale can be understood by the tropopause height modulation.

Zonal mean total ozone tends to show low (high) values about one year later than high (low) SST in the equatorial region (four year oscillation or FYO; Hasebe 1983). This is understood to be due to the advection effect of SST. The activated upward motion at the time of high SST would penetrate into the lower stratosphere. The air parcels cool adiabatically because of the lack of latent heat supply. Then, lower stratospheric temperature shows negative correlation with the SST (Reid *et al.*, 1989). If the vertical motion is maintained much longer than the radiative time-scale ($\simeq$ 1 month), the temperature anomalies are subject to radiative damping as in the case of the QBO. This diabatic heating must be coupled with the vertical motion. These processes are formulated into a mechanistic equation to model the total ozone variations associated with the advection effect of SST (See Hasebe, 1992, in detail). It should be noted that the tropospheric heating is proportional to the time derivative of ozone in the advection effect and to the ozone anomaly itself in the tropopause effect.

3.3 Annual cycle

The annual cycle of equatorial total ozone exhibits a maximum in September and a minimum in January accompanied by a stationary zonal wavenumber 1 structure with the phase of minimum located around 120°-150° E (Fig. 1). This component is tightly coupled with the altitude change of the tropopause. Although the location of the phase of minimum suggests the strong influence of SST on the tropopause height, the annual cycle of the tropopause height cannot be described solely by SST variations. Rather it is directly related to the lower stratospheric temperature field which may be understood by the asymmetrical seasonal variation of meridional heat transport by planetary waves. This suggests that the quasi-horizontal eddy transport responsible for the tropopause height changes also plays some role in the annual cycle of the equatorial total ozone.

4 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 one pattern; the zonal mean values are maximum around September and minimum around January. The wave 1 pattern is persistent over the year with minimum values between 140°E and 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. However, the vertical motions associated with the vertical shear of zonal wind (Plumb and Bell, 1982) need to be modified to fully describe the ozone advection.

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 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.

These variations of equatorial total ozone can be understood as being driven by two dynamical processes; the advection effect and the tropopause effect. The advection effect affects the zonal mean values of total ozone through vertical ozone advection by the diabatically driven mean meridional circulation. The diabatic heating comes from the radiational relaxation of temperature anomalies associated with the vertical gradients of mean zonal winds and the adiabatic ascent forced in the troposphere by latent heat release in convective systems. The tropopause effect affects the zonal wave component as well as the zonal mean value of total ozone by changing the altitude of the tropopause. Mechanistic equations which describe these dynamical processes are used together with the observed wind and SST to estimate total ozone variations. It is found that the zonal mean values of total ozone are dominated by the advection effect associated with the zonal wind QBO, although our preliminary investigations suggest that modification of the vertical velocity seems to be necessary by incorporating the feedback of the ozone QBO into diabatic heating. On the other hand, the zonal wave components are well described by the tropopause effect of SST. The annual cycle of equatorial total ozone can be understood by the tropopause height changes, although the annual cycle of tropopause height remains to be fully explained.

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