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Y.K. Leung, W.L. Chang & Y.W. Chan

Meteorology and Atmospheric Physics, Vol. 87, No. 4, 2004

(published online in November 2003)

Meteorol Atmos Phys (2003)
DOI 10.1007/s00703-003-0052-9

Meteorology and Atmospheric Physics
Printed in Austria

Hong Kong Observatory, Hong Kong, China

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Y. K. Leung, W. L. Chang, and **Y. W. Chan**

With 15 Figures

Received February, 2003; revised May 6, 2003; accepted September 11, 2003
Published online: November 28, 2003

Summary

Analysis of ozonesonde data shows that in the lower troposphere above Hong Kong, there is a relative maximum with respect to height in all seasons except winter. In the upper troposphere, there is with respect to height a relative minimum in the seasonally averaged ozone mixing ratio in winter. Ozone mixing ratios in the upper troposphere in winter and spring can be significantly enhanced by stratospheric intrusions associated with the passage of cold fronts and upper cut-off lows.

For Hong Kong, the seasonally averaged total ozone has the highest value in spring, and the lowest in winter. The seasonally averaged total tropospheric ozone also has the highest value in spring, but the lowest in summer. In a relative sense, total tropospheric ozone contributes most to the total ozone in spring and the least in summer.

The phase of the total ozone anomaly above Hong Kong is influenced by the Quasi-Biennial Oscillation (QBO), with the positive anomaly associated with the easterly phase of QBO, and the negative anomaly the westerly phase.

1. Introduction

Although chemically identical, ozone in different layers in the atmosphere exerts different influences on the well being of Man (WMO, 1998). In the stratosphere where approximately 90% of the atmosphere's ozone is found, ozone prevents the sun's ultra-violet radiation from reaching the surface of the Earth. In the troposphere ozone is a direct greenhouse gas (Mohnen et al, 1995; Prather et al, 2001), and the vertical redistribution of ozone can affect radiative forcing (Rajeevan, 1996). In the boundary layer which is typically the lowest 2 km or so of the atmosphere (Pasquill and Smith, 1983), ozone is a pollutant which harms the health of both Man and his crops.

WMO (1993) has strongly recommended the measurement of vertical distribution of ozone especially in the tropics where little is known of the critical chemical reactions that take place. Hong Kong lies on the south China coast in the tropics at a latitude of 22.3° N and a longitude of 114.2° E (Fig. 1). The south China coast is an area of fast economic growth thus making the identification of sources of ozone in the atmosphere above it of importance. To this end, the Hong Kong Observatory began operating balloon-borne ozonesondes once a month at its King's Park Meteorological Station in October 1993 to obtain the data necessary for better understanding the characteristics of ozone in the atmosphere above Hong Kong and its vicinity, and also as a contribution to the World Meteorological Organization's (WMO) Global Atmospheric Watch (GAW) programme by Hong Kong, China.

Ozonesonde operations have since also been conducted by the Hong Kong Observatory in support of National Aeronautics and Space Administration's (NASA) Pacific Exploratory

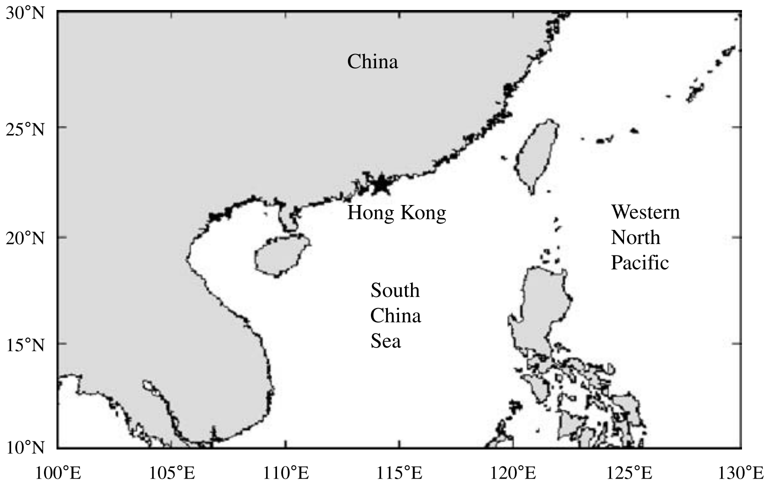

Fig. 1. The geographical location of Hong Kong

Mission West-B (PEM-West B) project in 1993–1994 as well as its Transport and Chemical Evolution over the Pacific (TRACE-P) project in 2000–2001 (see http://www-gte.larc.nasa.gov/trace/tracep.html for details). They have also been carried out for the Hong Kong Polytechnic University's atmospheric chemistry programme. Up to the end of 2001, over 270 profiles on the vertical distribution of ozone above Hong Kong have been obtained. These ozone profiles provide a unique dataset for characterizing vertical ozone distributions above Hong Kong and its vicinity.

Investigators of the features of these ozone profiles include Liu et al (1999) who pointed out that in spring, ozone profiles above Hong Kong often showed enhancements in ozone mixing ratios in the lower troposphere. They postulated that these enhancements were related to biomass burning activities in Southeast Asia. This relationship was studied by Chan et al (2000; 2003a) who utilized trajectory modelling and satellite imageries of fire counts, and by Liu et al (2002) who employed the GEOS-CHEM global three-dimensional chemical transport model as well as a trajectory model. The impact of the 1997 Indonesian forest fires on the vertical distribution of ozone above Hong Kong was assessed by Chan et al (2001). The characteristics of tropospheric ozone profiles observed above Hong Kong and two other sites in China (Kuming and Linan) during the spring of 2001 was compared by Chan et al (2003b).

Using the ozone profiles obtained between 1993 and 2001 by the Hong Kong Observatory, this paper examines some characteristics of the seasonally averaged ozone distributions or profiles above Hong Kong. It also demonstrates the influence of stratospheric intrusions on ozone mixing ratios in the upper troposphere above Hong Kong using case studies. Case studies are useful in the investigation of stratospheric intrusion events because of the episodic nature of these events (Austin and Midgley, 1994), and this paper presents one event associated with the passage of a cold front and another associated with an upper cut-off low. In these case studies, potential vorticity (PV) is employed as a tracer as high PV values are characteristic of tropospheric air of stratospheric origin (Danielsen, 1968; Appenzeller and Davies, 1992). As far as the authors can ascertain, this is the first time that stratospheric intrusions in the upper troposphere above the South China coastal area are documented via PV analysis. The climatology of stratospheric intrusions above the South China coastal area using Hong Kong's ozonesonde observations would be attempted as a separate study, the meteorological data required for such a climatological analysis not being presently available to the authors.

Furthermore, this paper compares the total ozone obtained from ozonesonde data with those from the Total Ozone Mapping Scatterometer (TOMS), analyzes the seasonal variation in total ozone and total tropospheric ozone above Hong Kong, and investigates the possible influence of the QBO on the interannual variation in total ozone above Hong Kong.

2. Ozone soundings

The ozonesondes used by the Hong Kong Observatory are of the electrochemical concentration cell (ECC) type. Each ozonesonde consists of an electrochemical cell which serves as ozone sensor, a non-reactive air pump, an electronic interface board, and a special version model RS 80-15GE Vaisala radiosonde (model RS 80-15FE was used between October 1993 and July 1997).

The ECC sensor has been widely used since the early 1970s, and its accuracy has been tested in a number of studies (e.g., Barnes et al, 1985; Komhyr et al, 1995). The sensors consist of two platinum electrodes immersed in potassium iodide (KI) solutions of concentration 1% (10 g of KI in 1000 ml of solution) contained in separate cathode and anode chambers.

The ozonesondes are launched with 1.5 kg or 3 kg rubber balloons and flown to a height that is normally over 30 km. Ozone mixing ratios as well as air pressure, air temperature, humidity and wind data are telemetered to the ground receiving system (Vaisala DigiCORA/MARWIN system) at King's Park Meteorological Station for analysis. The average ascent rate is 5 m/s and data is sampled every 2 seconds to give a mean vertical data resolution of about 10 m. Details of these ozonesonde operations can be found in Shun and Leung (1993).

Of the 270 ozone profiles obtained between 1993 and 2001, only those 181 which reached 30 km or above are selected for the present study. This is to ensure that the ozone layer has been captured as much as possible for the computation of total ozone. Total ozone is computed by integrating the ozone profiles from the surface to the top of the atmosphere. Likewise, total tropospheric ozone is obtained by integrating the ozone profiles with height from the surface to the tropopause.

The total ozone above balloon burst altitude is computed by extrapolating the ozone mixing ratio at burst altitude to the top of the atmosphere. The formula for calculating the total ozone X above burst altitude is given by

$$X = \frac{P\varepsilon}{g\rho}, \tag{1}$$

where P is the ozone partial pressure at burst altitude, ε is the ratio of molar masses of ozone to air and ρ is the ozone density under standard atmospheric condition at 1013.25 hPa and 273.15 K (Godson, 1962). The total ozone determined by this formula is comparable with that obtained by using the SBUV ozone climatology data proposed by McPeters et al (1997) for the region 20° N to 30° N.

3. Characteristics of ozone profiles above Hong Kong

3.1 Ozone profiles

In this study, the seasons spring, summer, autumn and winter refer respectively to the months March to May, June to August, September to November, and December to February. Seasonally averaged profiles for spring, summer, autumn and winter are constructed based on 56, 29, 42 and 54 ozone profiles, respectively.

The seasonally averaged ozone profiles above Hong Kong for the atmosphere as a whole are given in Fig. 2a–d. Following Fujiwara et al (2000), the vertical resolution used in this figure is 200 metres.

Figure 2 shows that the ozone mixing ratio has a maximum at an altitude between 30 and 33 km in the stratosphere. The magnitude of this maximum is the largest in spring and summer, with a value exceeding 9.0 ppmv. It falls to 8.8 ppmv in autumn, and further down to 7.8 ppmv in winter.

The temperature profiles in Fig. 2a–d shows that the seasonally averaged height of the tropopause above Hong Kong is about 17 km, and there is little interseasonal variation. Tropopause is defined as the lowest level at which the lapse rate decreases to $2^\circ\,C\,km^{-1}$ or less (WMO, 1960). Following Liu et al (2002) whose results for stratospheric intrusion into the upper troposphere above Hong Kong will be referred to in Subsect. 3.3 below, for descriptive purposes the "lower troposphere" is taken in this study as that part of the atmosphere below 3 km (700 hpa) and includes the boundary layer, the "middle troposphere" between 3 and 10 km, (700 hpa to 300 hpa), and the "upper troposphere" between 10 km and the tropopause (300 hpa to about 100 hpa) between which altitudes the jet streams reside (Palmén and Newton, 1969).

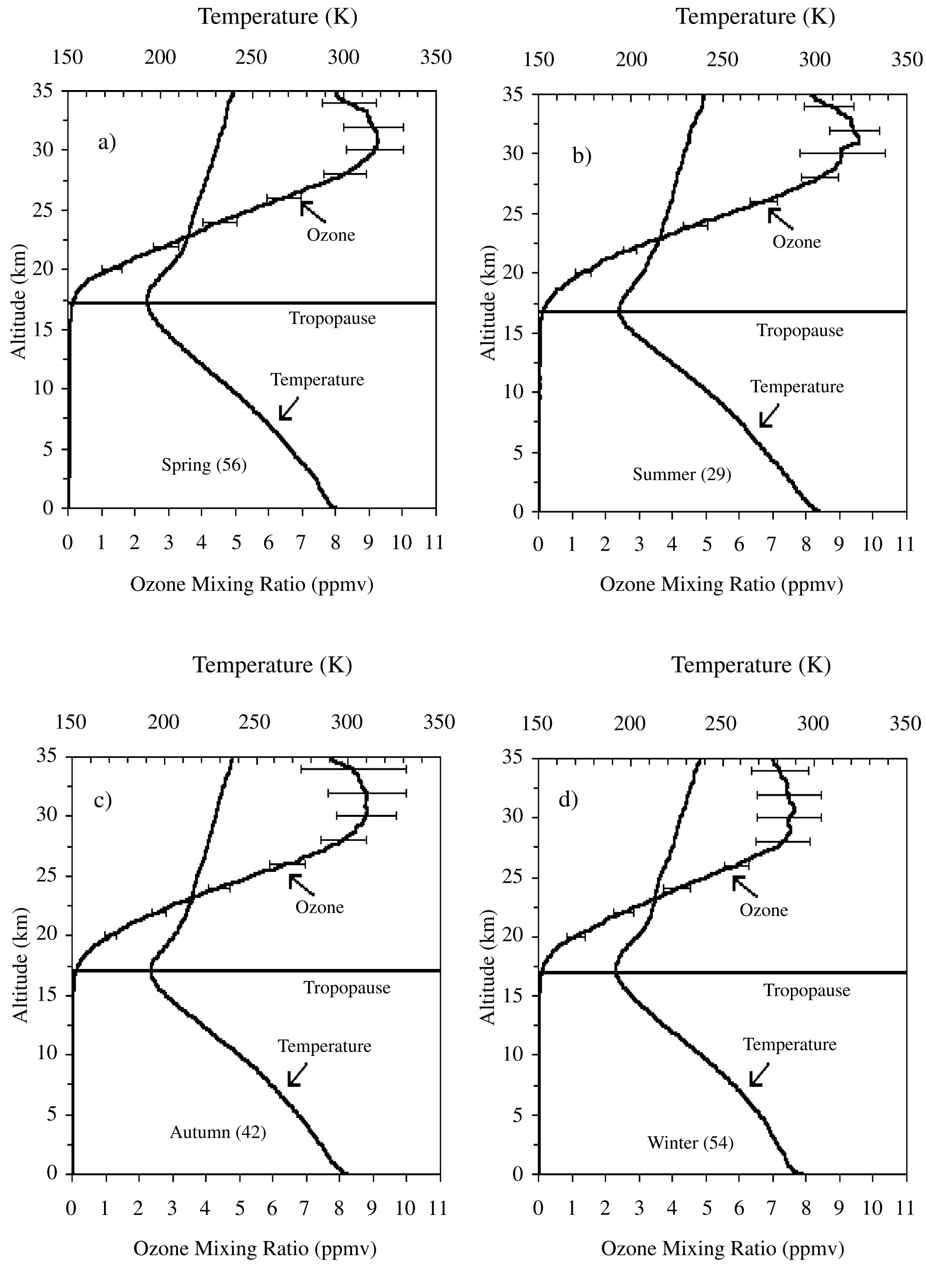

Fig. 2. Seasonally averaged ozone profiles above Hong Kong for (**a**) spring, (**b**) summer, (**c**) autumn, and (**d**) winter. The error bars show the seasonal averaged ozone mixing ratios plus/minus one standard deviation at selected altitudes. The numbers in brackets are the number of individual profiles used to derive the seasonally averaged profiles

3.2 Tropospheric features

3.2.1 Variation with height for each season

The seasonally averaged ozone profiles in the troposphere are plotted in Fig. 3, the vertical resolution in which is again 200 m. Figure 3a shows that in the lower troposphere in spring, there is with respect to height a relative maximum in ozone mixing ratio at about 3 km. The magnitude of the relative maximum in ozone mixing ratio is about 70 ppbv. The seasonally averaged relative humidity at 3 km altitude is over 60%, too high for the air associated with this relative maximum to be of stratospheric origin. Backward air trajectories and fire counts deduced from the optical Along Track Scanning Radiometer (ATSR) sensor on board the European ERS-2 satellite all suggest that this air is likely to have come from continental Southeast Asia where it picked up ozone precursors produced by biomass burning before arriving at Hong Kong (Liu et al, 1999; Chan et al, 2000; 2003a).

Figure 3b and c shows that in the lower troposphere in summer as well as autumn, there is a relative maximum with respect to height at about

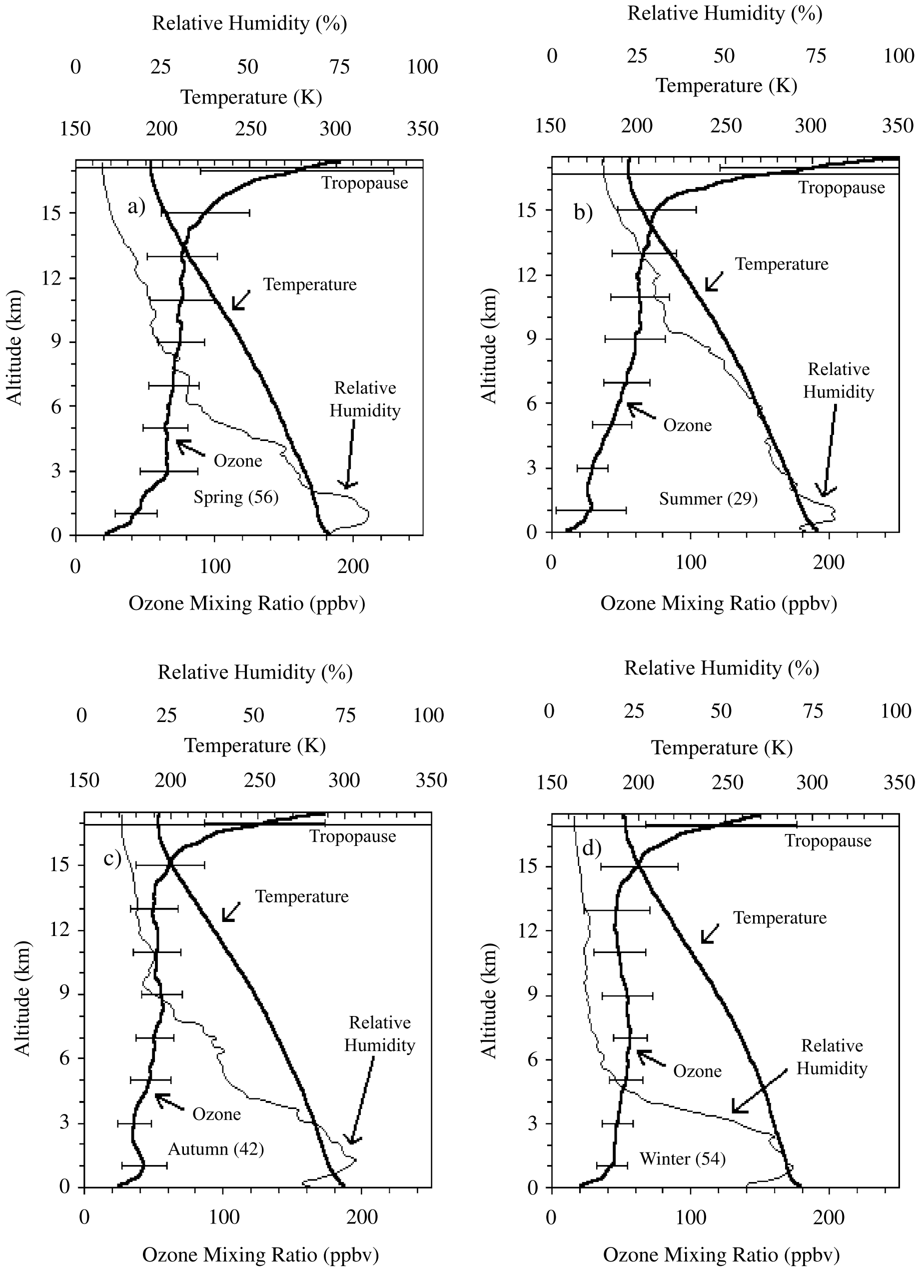

Fig. 3. Seasonally averaged ozone profiles in the troposphere above Hong Kong in (**a**) spring, (**b**) summer, (**c**) autumn, and (**d**) winter. The error bars show the seasonal averaged ozone mixing ratios plus/minus one standard deviation at selected altitudes. The numbers in brackets are the number of individual profiles used to derive the seasonally averaged profiles

1 km. The magnitude of this relative maximum is about 30 ppbv in summer, and about 45 ppbv in autumn. For each of these two seasons, the relative maximum in ozone mixing ratio coincides with a relative maximum in relative humidity. The simultaneous occurrence of high ozone mixing ratio and high relative humidity (about 80%) indicates that the ozone has come either from photochemical production or convection from the polluted boundary layer (Tsutsumi and Makino, 1995; Thouret et al, 2000).

In winter, the seasonally averaged ozone mixing ratio increases sharply from about 20 ppbv at the ground to about 45 ppbv at an altitude of about 1 km (Fig. 3d). It then continues to increase with height but at a much slower rate, reaching a relative maximum of about 57 ppbv at the altitude of 7 km in the middle troposphere. Between the ground and 3 km, there is a relative maximum in relative humidity with a value of about 70%. This again suggests ozone at these altitudes has its source in tropospheric transport or production.

Above 7 km, the ozone mixing ratio decreases gradually and attains a relative minimum at just above 12 km in the upper troposphere. The case studies conducted by Chan et al (1998) and Liu et al (2002) suggest that the occurrence of the relative minimum is related to the northward transport to the south China coast of clean maritime air which had first been lifted by convection to the upper troposphere. Newell (1997) has also proposed a similar explanation for the low ozone mixing ratios in the upper troposphere over the western North Pacific observed by airborne lidar in PEM-West B.

3.2.2 Interseasonal variation at different altitude

Figure 4 shows a plot of the seasonal variation of ozone at different altitudes in the troposphere. In the lower, middle as well as the upper troposphere, ozone mixing ratio is the highest in spring among the four seasons. Ozone mixing ratio is found lowest in summer for the lower troposphere but winter for the upper troposphere. In the lower troposphere, ozone mixing ratio ranges from about 28 ppbv in summer to 44 ppbv in spring at 1 km, and 30 ppbv to 67 ppbv at 3 km. As height increases and for altitude 9 km or above, lowest ozone mixing ratio is found in winter instead of summer. In the upper troposphere, ozone mixing ratio ranges from 47 ppbv in winter to 77 ppbv in spring at 12 km, and 63 ppbv to 93 ppbv at 15 km.

3.2.3 Total tropospheric ozone

The time series of monthly averaged total tropospheric ozone in Hong Kong is shown in Fig. 5. It

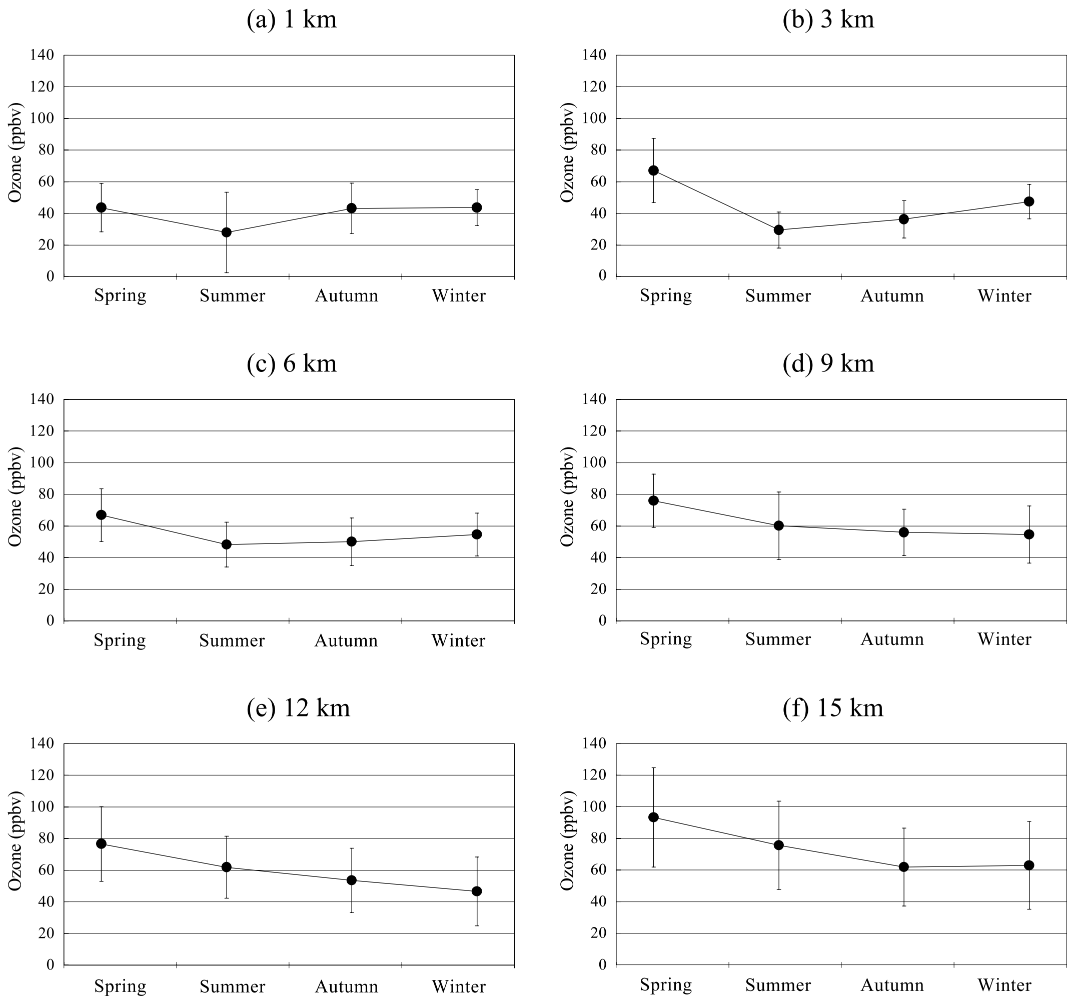

Fig. 4. Seasonal variation of ozone mixing ratio at different altitudes in the troposphere: (**a**) 1 km, (**b**) 3 km, (**c**) 6 km, (**d**) 9 km, (**e**) 12 km, and (**f**) 15 km. The error bars show the seasonal averaged ozone mixing ratios plus/minus one standard deviation

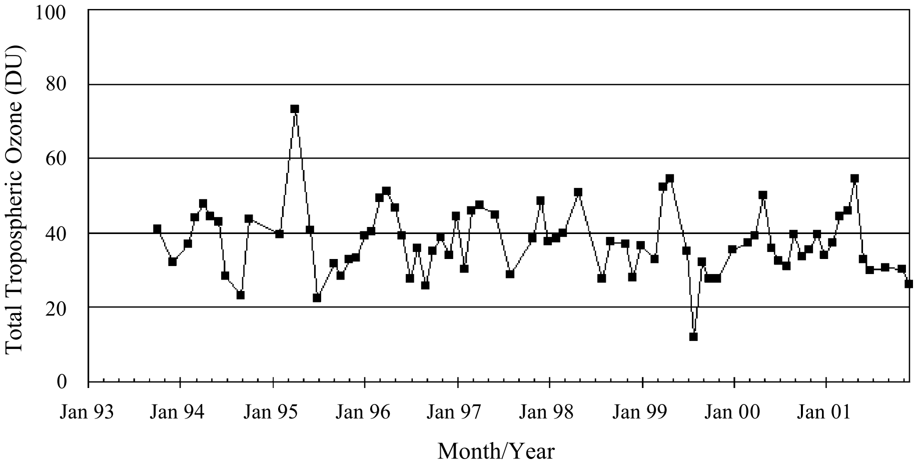

Fig. 5. Variation of monthly averaged total tropospheric ozone

can be seen that in general, total tropospheric ozone reaches a maximum in spring and a minimum in summer. The monthly averaged total tropospheric ozone above Hong Kong ranges from 12 to 73 Dobson Units (DU). Seasonally, total tropospheric ozone above Hong Kong has an average of 48 DU in spring, 33 DU in summer, 34 DU in autumn and 36 DU in winter.

3.3 Stratospheric intrusions

The climatology of the occurrence of stratospheric intrusions into the tropical upper troposphere has been studied by Waugh and Polvani (2000) using the NCAR/NCEP reanalysis data between 1980 and 1997. They define intrusion events in the tropics by absolute values of PV exceeding 2 units (1 PV unit $= 10^{-6}\,m^2\ s^{-1}{}^\circ K\ kg^{-1}$) at 10 °N or 10 °S. Based on this criterion, Waugh and Polvani (2000)'s study shows that in the northern hemisphere, stratospheric intrusions occur mainly during the northern winter and over the Pacific between the longitudes 180° E and 260° E. For that part of the tropics in the vicinity of Hong Kong's longitude, stratospheric intrusion events do not seem to be evident (their figure 2b).

Using the global GEOS-CHEM model and trajectory analysis, Liu et al (2002) attributed the enhanced ozone mixing ratios observed in the upper troposphere above Hong Kong on 6 January 1997 to stratospheric intrusion. On that day, the 06 UTC ozonesonde observations show ozone mixing ratios increasing sharply from about 10 km upwards, reaching a maximum of 175 ppbv between about 12 km to 14 km

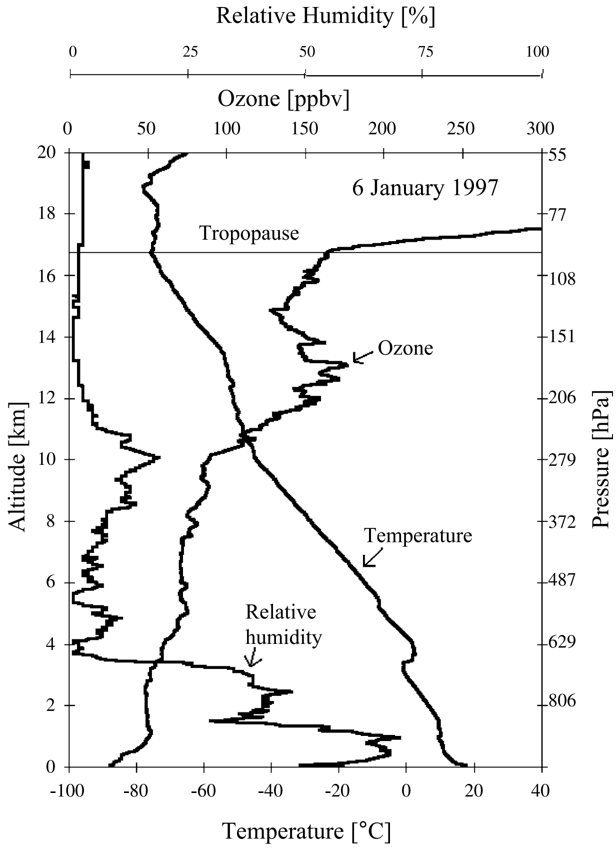

Fig. 6. Ozone profile on 6 January 1997

(Fig. 6). This is about 3.5 times the winter average for these altitudes (Fig. 3d), and the largest ozone mixing ratio observed in the upper troposphere above Hong Kong to-date.

Liu et al's (2002) conclusion is supported by PV analysis, the results of which are shown in Fig. 7. One can see from this figure that at

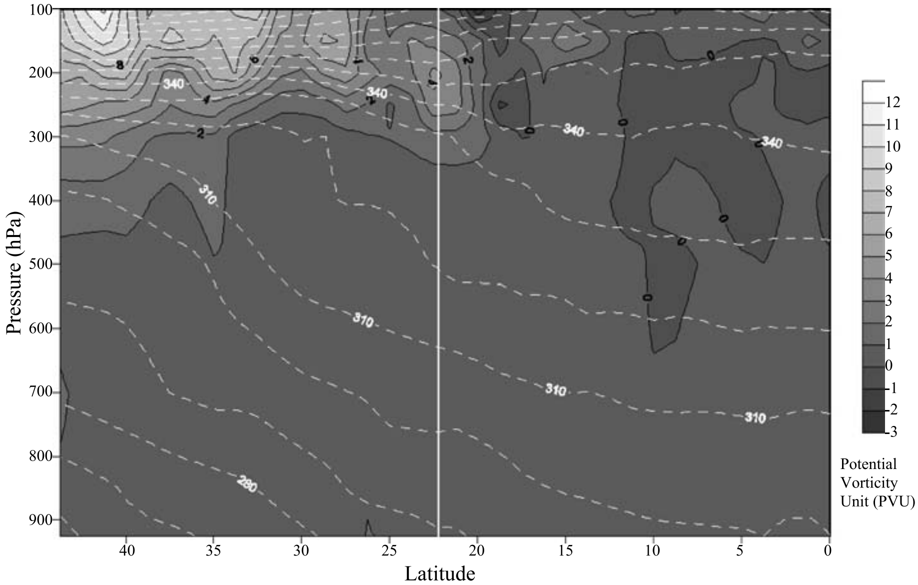

Fig. 7. Meridional cross section of potential vorticity along 113.75° E at 00 UTC on 6 January 1997. Black lines are the potential vorticity in PV units, dashed white lines potential temperature in °K. Hong Kong's latitude is marked by the vertical line in white

Hong Kong's latitude (22.3° N), there is between about 300 hPa (9.5 km) and 120 hPa (15.4 km) a tongue of air with PV of 2 PV Units or more and reaching as much as 4 PV Units. These altitudes coincide with those between which ozone mixing ratios are enhanced, and indicate the air at these altitudes has its origin in the stratosphere. In Fig. 7, PV is calculated from

$$PV = -g(\zeta + f)\partial\theta/\partial p, \qquad (2)$$

(Gill, 1990) where ζ is the relative vorticity, f ($=5.6 \times 10^{-5}\,s^{-1}$ for Hong Kong) the Coriolis parameter, θ the potential temperature, p the pressure and g the gravitational acceleration. The wind and temperature data are obtained from Japan Meteorological Agency's (JMA) 1.25° resolution analyzed fields at 00UTC, and the calculations are made in the 113.75° E meridional plane which is the one closest to Hong Kong in JMA's grid.

The stratospheric intrusion on 6 January 1997 is associated with the passage of surface cold fronts across the south China coast (Fig. 8a and b) and the presence subtropical jets at 200 hPa aloft (Fig. 9a and b). That stratospheric intrusions often take place in the vicinity of cold fronts have been noted by Appenzeller and Davies (1992) as well as others.

Another instance of stratospheric intrusion appears to have occurred on 6 May 1998. Figure 10 shows that at 06 UTC that day, ozone

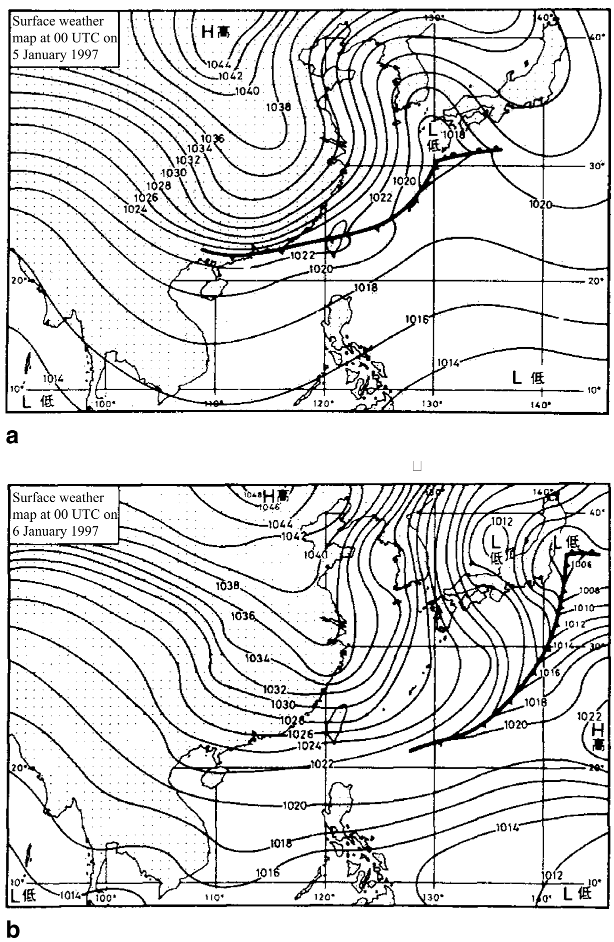

Fig. 8. Surface weather charts at 00 UTC on (**a**) 5 January 1997, and (**b**) 6 January 1997 showing the passage of a cold front across the south China coast

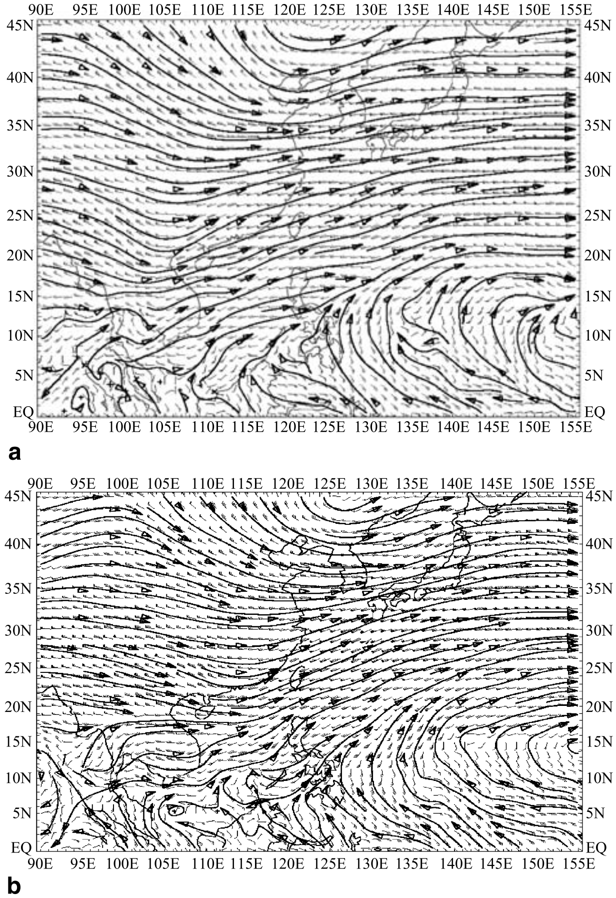

Fig. 9. 200 hPa analyzed wind fields valid at 00 UTC on (**a**) 5 January 1997, and (**b**) 6 January 1997 (based on Japan Meteorological Agency's analysis) showing the subtropical jet over the south China coast and the northern part of the South China Sea

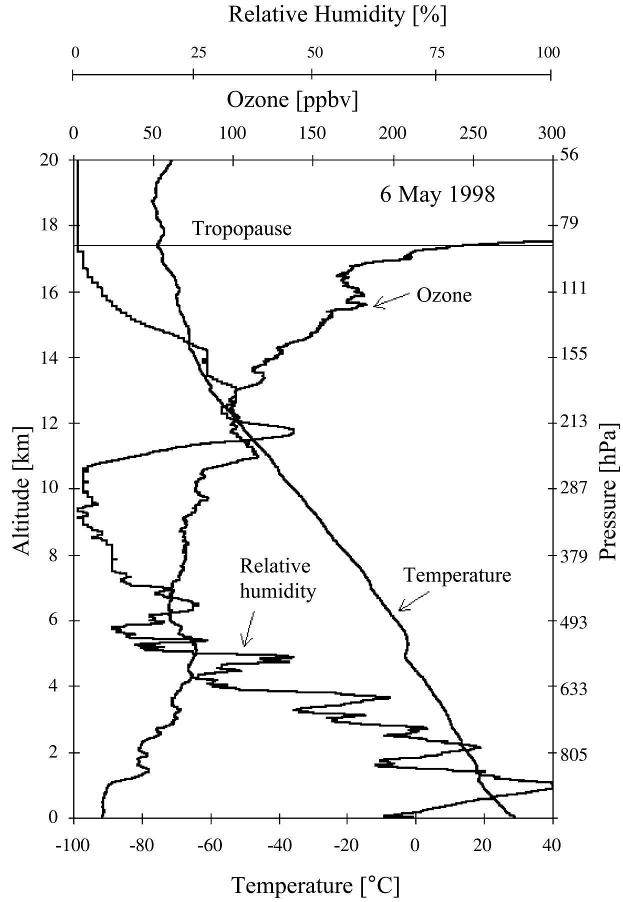

Fig. 10. Ozone profile on 6 May 1998

mixing ratios increased sharply from about 13 km to a relative maximum of over 150 ppbv between about 15 km to 16 km. This is about 1.5 times the spring average for these altitudes (Fig. 3a).

PV analysis shows that air with more than 2 PV units is found in the upper troposphere above 160 hPa (14 km) at Hong Kong's latitude (Fig. 11). The event of 6 May 1998 is associated with the presence of an upper cut-off low in the southeastern China (Fig. 12a and b). This cut-off low developed in a deepening westerly trough. A similar instance of stratospheric intrusion associated with an upper cut-off low above Japan has been presented by Austin and Midgley (1994).

In neither the 6 January 1997 nor the 6 May 1998 events did PV values of 2 PV Units or more extend to 10° N. This possibly explains why these two events do not seem to be picked up by the analysis of Waugh and Polvani (2000). It would be useful to obtain the climatology of stratospheric intrusions above the south China coastal area to add detail to the information obtained by Waugh and Polvani (2000) for the tropics, as well as to provide insight into how often are ozone mixing ratios in the upper troposphere above the south China coastal area influenced by such intrusions. This is the subject of a separate study.

4. Total ozone

4.1 Comparison with TOMS data

Before analyzing the seasonally averaged total ozone over Hong Kong, a comparison is made between the monthly averaged total ozone derived from the ozonesondes and that derived

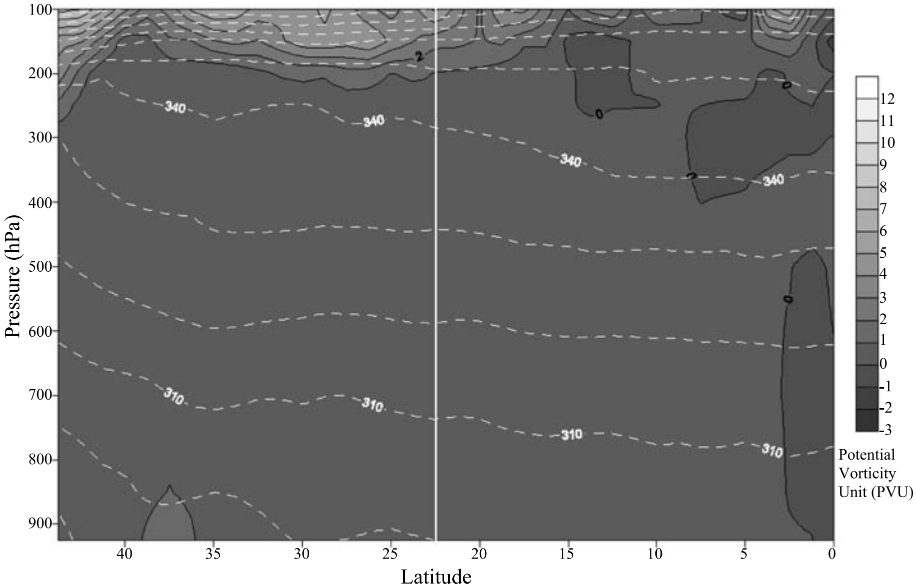

Fig. 11. Meridional cross section of potential vorticity along 113.75° E at 00 UTC on 6 May 1998. Black lines are the potential vorticity in PV units, dashed white lines potential temperature in °K. Hong Kong's latitude is marked by the vertical line in white

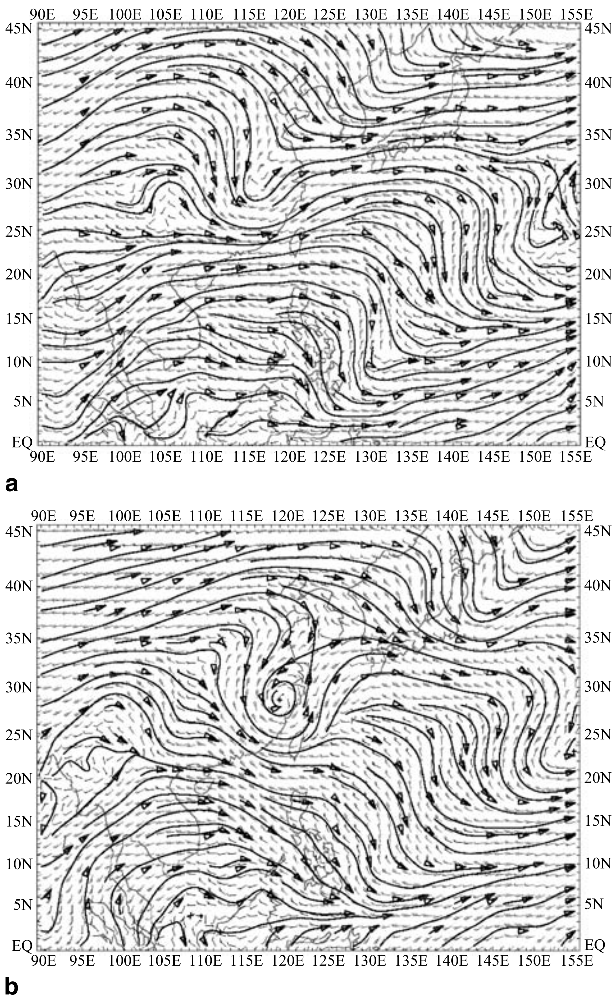

Fig. 12. 200 hPa analyzed wind fields valid at 00 UTC on (**a**) 5 May 1998, and (**b**) 6 May 1998 (based on Japan Meteorological Agency's analysis) showing an upper cut-off low in the southeastern China

from the Total Ozone Mapping Spectrometer (TOMS) aboard the Earth Probe satellite. TOMS data between July 1996 and December 2001 are obtained from http://toms.gsfc.nasa.gov/ozone/ozoneother.html.

The total ozone derived from the ozonesondes seems to compare or "benchmark" well against the total ozone above Hong Kong derived from TOMS. Correlation between the ozonesonde and the TOMS total ozone data is high (Fig. 13). The correlation coefficient is 0.84 and significant at 0.01 level. The absolute difference between the corresponding monthly values of the ozonesonde and TOMS data are small, with an average of 13.4 DU or 5% relative to TOMS data.

4.2 Seasonal variations in total ozone

The seasonally averaged total ozone above Hong Kong is obtained by averaging the total ozone derived from the profiles in the season. It has a value of 290 DU in spring, 286 DU in summer, 269 DU in autumn and 245 DU in winter. That is, total ozone in Hong Kong has a maximum in spring and minimum in winter. The spring maximum is a common characteristics of both mid-latitude and tropical total ozone, while the winter minimum is characteristic of tropical total ozone. The minimum in total ozone in the mid-latitudes occurs in autumn (Mani, 1991).

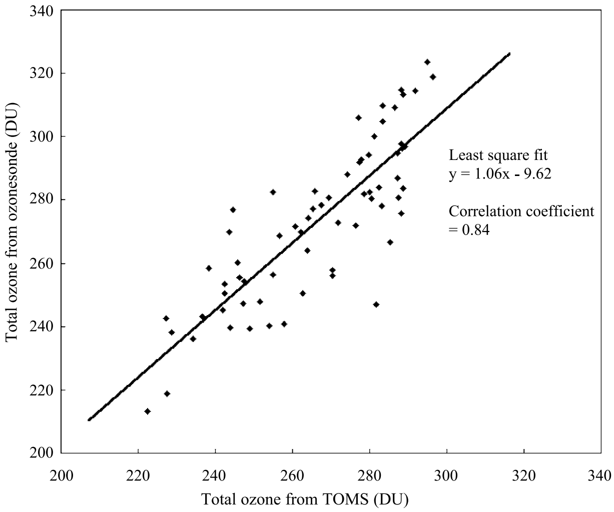

Fig. 13. Correlation between the total ozone obtained from ozonesondes and TOMS

4.3 Contribution of total tropospheric ozone to total ozone

Dividing the seasonally averaged total tropospheric ozone in Subsect. 3.2.3 by the seasonally averaged total ozone for each season gives the contribution of total tropospheric ozone to total ozone: 16% in spring, 11% in summer, 13% in autumn and 15% in winter. Thus, in a relative sense, total tropospheric ozone contributes most to total ozone above Hong Kong in spring, and the least in summer. These percentages are similar to those found by Chan et al (1998) using ozone profile data between October 1993 and 1996. The average of all the four seasons is 14%.

4.4 QBO signal

Spectral analysis using the five-point Hamming window is carried out on the total ozone above Hong Kong derived from the ozonesondes and TOMS. Results show that total ozone anomalies obtained from ozonesondes have a periodicity of about 27 months after the annual cycle is filtered out by forming 13-month running averages (Fig. 14a). This periodicity is suggestive of the influence of QBO on total ozone anomalies above Hong Kong. The result also agrees with that of Tung and Yang (1994) who found that between 30° N and 30° S, the QBO is the dominant periodicity in total ozone anomalies apart from seasonal cycle. The total ozone anomalies above Hong Kong as obtained from TOMS data similarly show the QBO signal (Fig. 14b).

Furthermore, for both ozonesonde and TOMS data, the positive phase in total ozone anomalies above Hong Kong is generally associated with the easterly phase of the QBO, and the negative phase in total ozone anomalies with the westerly phase of the QBO (Fig. 15). This relationship is consistent with that found by Tung and Yang (1994) for the region north of 12° N from analyses of TOMS ozone data for global ozone anomaly patterns, and with that of Logan et al (2003) who used TOMS ozone data and also ozonesonde data between 20° N and 20° S which are outside Hong Kong's latitude.

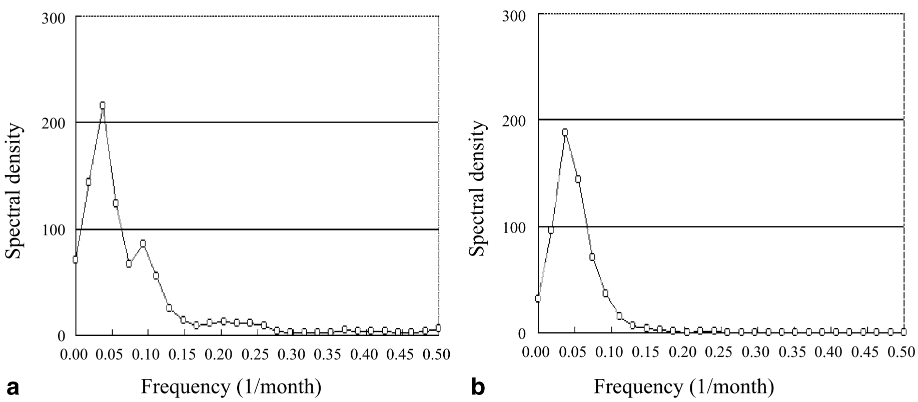

Fig. 14. Spectral analysis of time series of 13-month running averaged total ozone anomalies above Hong Kong based on (**a**) ozonesonde, and (**b**) TOMS data

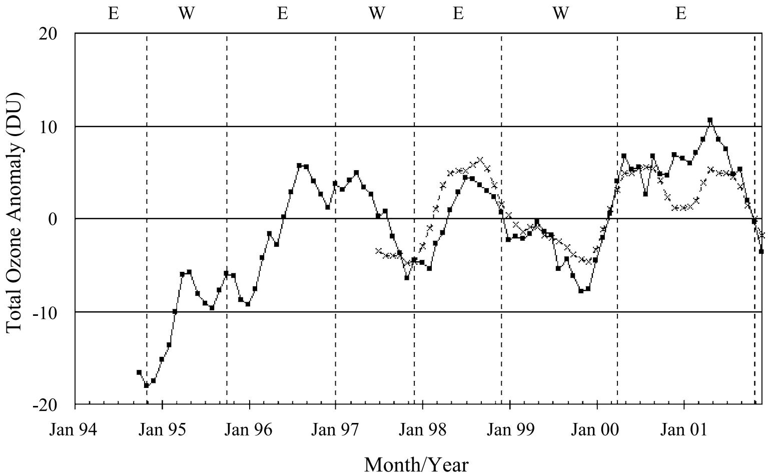

Fig. 15. Variation of the 13-month running averaged total ozone anomalies above Hong Kong with respect to the easterly and westerly phases of QBO (—■— ozonesonde data, —✕— TOMS data). Classifications of the easterly (E) and westerly (W) phases are based on the signs of the 30 hPa equatorial zonal wind data obtained from the NOAA's website http://www.cdc.noaa.gov/climateindices

5. Conclusions

In the atmosphere above Hong Kong, the peak value in the seasonally averaged vertical profile of ozone mixing ratio is found in the stratosphere at an altitude between 30 and 33 km. This peak value ranges from 7.8 ppmv in winter to over 9.0 ppmv in spring and summer.

In the lower troposphere, the seasonally averaged vertical ozone profiles show a relative maximum with respect to height at an altitude of about 3 km in spring, and 1 km in summer and autumn. The high relative humidity associated with these relative maxima suggests that the relative maxima occurring in these three seasons in the lower troposphere is likely to be of tropospheric origin.

In the seasonally averaged ozone profile of winter, there is a relative minimum in ozone mixing ratio at just above 12 km. This relative minimum is probably brought about by the northward transport to the South China coast of clean maritime air which had first been lifted by convection to the upper troposphere.

Potential vorticity analysis suggests that Hong Kong is susceptible to the influence of stratospheric intrusions which can result in large ozone enhancements in the upper troposphere in winter and spring.

The seasonally averaged total ozone above Hong Kong has a maximum of 290 Dobson Units in spring and a minimum of 245 Dobson Units in winter. The seasonally averaged total tropospheric ozone also has a maximum of 48 Dobson Units in spring but a minimum of 33 Dobson Units in summer. In a relative sense, total tropospheric ozone contributes most, about 16%, to total ozone in spring and the least, about 11% in summer.

Spectral analysis shows that total ozone anomaly above Hong Kong is influenced by QBO. The easterly phase of the QBO is generally associated with positive anomalies in total ozone above Hong Kong, and the westerly phase negative anomalies.

Acknowledgements

The authors would like to thank Ms. Y. Y. Cheng, Ms. P. C. Yu, Ms. M. Y. Leung and Mr. Y. H. Lau of the Hong Kong Observatory for the preparation of the figures and the computation of potential vorticity. The authors would also like to thank the two anonymous reviewers for their comments.

References

Appenzeller C, Davies HC (1992) Structure of stratospheric intrusion into the troposphere. Nature 358: 570–572

Austin JF, Midgley RP (1994) The climatology of the jet stream and stratospheric intrusions of ozone over Japan. Atmos Environ 28: 39–52

Barnes RA, Bandy AR, Torres AL (1985) Electrochemical concentration cell ozonesonde accuracy and precision. J Geophys Res 90: 7881–7887

Chan LY, Liu HY, Lam KS, Wang T, Oltmans SJ, Harris JM (1998) Analysis of the seasonal behavior of tropospheric ozone at Hong Kong. Atmos Environ 32: 159–168

Chan LY, Chan CY, Liu HY, Christopher S, Oltmans SJ, Harris JM (2000) A case study on the biomass burning in Southeast Asia and enhancement of tropospheric ozone over Hong Kong. Geophys Res Lett 27: 1479–1482

Chan CY, Chan LY, Zheng YG, Harris JM, Oltmans SJ, Christopher S (2001) Effects of 1997 Indonesian fires on tropospheric ozone enhancement, radiative forcing, and temperature change over the Hong Kong region. J Geophys Res 106: 14875–14885

Chan CY, Chan LY, Harris JM, Oltmans SJ, Blake DR, Qin Y, Zheng YG, Zheng XD (2003a) Characteristics of biomass burning emission sources, transport, and chemical speciation in enhanced tropospheric ozone profile over Hong Kong. J Geophys Res 108(0) (DOI: 10.1029/2001JD001555)

Chan CY, Chan LY, Chang WL, Zheng YG, Cui H, Zheng XD, Qin Y, Li YS (2003b) Characteristics of tropospheric ozone profile and implications for the origin of ozone over subtropical China in the spring of 2001. J Geophys Res 108: 8800 (DOI: 10.1029/2003JD003427)

Danielsen EF (1968) Stratospheric – tropospheric exchange based on radioactivity, ozone and potential vorticity. J Atmos Sci 25: 502–518

Fujiwara M, Kazuyuki K, Toshihiro O, Shuji K, Takuki S, Ninong K, Slamet S, Agus S (2000) Seasonal variations of tropospheric ozone in Indonesia revealed by 5-year ground-based observations. J Geophys Res 105: 1879–1888

Gill E (1990) Atmosphere-ocean dynamics. Harcourt Brace, 662 pp

Godson WL (1962) The representation and analysis of vertical distributions of ozone. Q J R Met Soc 88: 220–232

Komhyr WD, Barnes RA, Brothers GB, Lathrop JA, Opperman DP (1995) Electrochemical concentration cell ozonesonde performance evaluation during STOIC 1989. J Geophys Res 100: 9231–9244

Liu HY, Chang WL, Oltmans SJ, Chan LY, Harris JM (1999) On springtime high ozone events in the lower troposphere from SE Asian biomass burning. Atmos Environ 33: 2403–2410

Liu HY, Jacob DJ, Chan LY, Oltmans SJ, Bey I, Yantosca RM, Harris JM, Duncan BN, Martin RV (2002) Sources of tropospheric ozone along the Asian Pacific Rim: An analysis of ozonesonde observations. J Geophys Res 107: 4573 (DOI:10.1029/2001JD002005)

Logan JA, Jones DBA, Megretskaia IA, Oltmans SJ, Johnson BJ, Vomel H, Randel WJ, Kimani W, Schmidlin FJ (2003) Quasibiennial oscillation in tropical ozone as revealed by ozonesonde and satellite Data. J Geophys Res 108: 4244 (DOI:10.1029/2002JD002170)

Mani A (1991) Ozone measurements in the tropics, in ozone depletion implications for the tropics. University of Science Malaysia and United Nations Environment Programme (Llyas M, ed), pp 84–97

McPeters RD, Labow GJ, Johnson BJ (1997) An SBUV ozone climatology for balloonsonde estimation of total column ozone. J Geophys Res 102: 8875–8885

Mohnen VA, Walter G, Wang WC (1995) The potential role of tropospheric ozone as a climate gas. WMO Bull 44: 38–42

Newell RE, Browell EV, Davis DD, Shaw SC (1997). Western Pacific tropospheric ozone and potential vorticity: Implications for Asian pollution. Geophys Res Lett 24: 2733–2736

Palmén E, Newton CW (1969) Atmospheric circulation systems. Academic Press, 603 pp

Pasquill F, Smith FB (1983) Atmospheric diffusion, 3rd ed. Ellis Horwood, 437 pp

Prather M, Ehhalt D et al (2001) Atmospheric chemistry and greenhouse gases. In: Climate Change 2001 – the Scientific Basis (Houghton JT et al, eds). Cambridge University Press, pp 239–287

Rajeevan M (1996) Climate implications of the observed changes in ozone vertical distribution. Int J Climatol 16: 15–22

Shun CM, Leung KS (1993) The first radioactivity and ozone soundings in Hong Kong. HK Met Soc Bull 3: 21–27

Thouret V, Cho YN, Newell RE, Marenco A, Smit GJ (2000) General characteristics of tropospheric trace constituent layers observed in the MOZAIC program. J Geophys Res 105: 17379–17392

Tsutsumi Y, Makino Y (1995) Vertical distribution of the tropospheric ozone over Japan: the origin of the ozone peaks. J Met Soc Japan 73: 1041–1058

Tung KK, Yang H (1994) Global QBO in circulation and ozone. Part I: reexamination of observational evidence. J Atmos Sci 51: 2699–2707

Waugh DW, Polvani LM (2000) Climatology of intrusions into the upper tropical troposphere. Geophys Res Lett 27: 3857–3860

WMO (1960) Guide to Climatological Practices. World Meteorological Organization No. 100

WMO (1993) Report of the Third Session of the EC Panel of Expert/CAS Working Group on Environmental Pollution and Atmospheric Chemistry. WMO/TD-No. 555. World Meteorological Organization, Geneva, Switzerland

WMO (1998) Scientific Assessment of Ozone Depletion: 1998. World Meteorological Organization Global Ozone Research and Monitoring Project-Report No. 144

Authors' address: Y. K. Leung, W. L. Chang, Y. W. Chan, Hong Kong Observatory, 134A Nathan Road, Kowloon, Hong Kong, China (E-mail: jykleung@hko.gov.hk)