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Development and Preliminary Evaluation of a Double-cell Ozonesonde

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ABSTRACT

Ozonesondes are widely used to obtain ozone concentration profiles from the surface to the upper atmosphere. A kind of double-cell ozonesonde has been developed at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (named the "IAP ozonesonde") based on previous experience over the past 20 years of developing the singlecell GPSO3 ozonesonde. The IAP ozonesonde is of the Electrochemical Concentration Cell (ECC) type. A detailed description of the IAP ozonesonde is firstly provided in the present paper, followed by a presentation of results from a series of launches carried out to evaluate its performance. The analysis involved comparing its observations with measurements from the GPSO3 and ECC ozonesondes (Model type ENSCI-Z) as well as a Brewer spectrophotometer. The results showed that the IAP ozonesonde is a vast improvement over the GPSO3 ozonesonde, able to capture vertical ozone structures very well and in good agreement with ECC ozonesonde measurements. The average difference in the ozone partial pressure between the IAP and ECC ozonesondes was 0.3 mPa from the surface to 2.5 km, close to zero from 2.5 to 9 km and generally less than 1 mPa for layers higher than 9 km. The apparent deviation is likely caused by a decreasing pump flow rate in the IAP ozonesonde which needs further improvement. The total ozone amounts measured by the IAP ozonesonde profiles were highly comparable with the Brewer data with a relative difference of 6%. The development of the IAP ozonesonde and its strong performance will surely accelerate the process of conventional observations of ozone profiles over China in the near future as well as provide more data for ozone research in general.

Key words: ozonesonde, development, evaluation, performance

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1. Introduction

In the troposphere, ozone is one of the major greenhouse gases, and its presence can impact human health and ecosystems. Meanwhile, stratospheric ozone plays an important role in the Earth system because it absorbs ultraviolet light from the sun. Atmospheric ozone is vital for the atmospheric environment, ecological balance, and climate change. Therefore, accurate observational data are urgently required to investigate the distribution of ozone, its trends of change, levels of depletion, and the associated climatic and environmental effects (Farman et al., 1985; Zhou and Luo, 1994).

The ozonesonde is a small, lightweight and compact balloon-borne instrument, which is interfaced to a standard meteorological radiosonde for data transmission to a ground receiver. The ozonesonde is one among a number of important instruments able to provide both campaign-based intensive measurements as well as long-term observations of ozone partial pressure with high vertical resolution (Thompson et al., 2003). Many countries have been conducting ozonesonde measurements and sending the data to the World Ozone and Ultraviolet Radiation Data Center (WOUDC). This global network of ozone sounding stations has resulted in the longest available time series of vertical ozone distribution from the surface to layers higher than 30 km (Thompson et al., 2007; Vömel and Diaz, 2010), and the ozone data it provides are widely employed to study photochemical and dynamical processes in the atmosphere and to evaluate satellite measurements (Thompson et al., 2011).

Three major types of ozonesondes have been the most widely used; namely, the Brewer-Mast (BM) (Brewer and Milford, 1960), the electrochemical concentration cell (ECC) (Komhyr, 1969), and the KC ozonesonde (Kobayashi and

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Toyama, 1966). Although these instruments were developed based on similar electrochemical methods, each has its own specific design (Smit et al., 2013). The ECC ozonesonde is composed of two half cells, while a single-cell technique is used for both the Brewer-Mast and KC ozonesondes. The World Meteorological Organization (WMO) has performed test campaigns, such as the Juelich Ozonesonde Intercomparison Experiment (JOSIE) and the Balloon Experiment on Standards for Ozonesondes (BESOS), to investigate their precision, accuracy and response as a function of altitude. The JOSIE was conducted three times in Juelich, Germany, in 1996, 1998 and 2000. The different types of ozonesonde were tested under a variety of simulated conditions in an environmental simulation chamber, and an accurate ozone UV-photometer was used to evaluate their performance (Smit and Kley, 1998; Smit and Sträter, 2004a, 2004b; Smit et al., 2007). The BESOS was held at the University of Wyoming at Laramie, USA, in 2004, and aimed to test the JOSIE results in the field by a balloon flight in the real atmosphere (Deshler et al., 2008). Both the JOSIE (Smit et al., 2007) and BESOS (Deshler et al., 2008) proved that the accuracy of the ECC ozonesonde was better than that of both the BM and KC ozonesondes—a result that was also confirmed by Smit and Kley (1998), Logan (1999), and Thompson et al. (2003).

Given the better performance of the ECC ozonesonde, it has been used in place of the KC96 ozonesonde in the Japanese ozone sounding network since 2011 (Smit et al., 2013). The BM ozonesonde has also been replaced by the ECC ozonesonde at many European stations, e.g. Uccle, Belgium, and Payerne, Switzerland (Stübi et al., 2008). In China, the single-cell GPSO3 ozonesonde was developed more than 20 years ago (Wang et al., 2003; Xuan et al., 2004). It has been used in Beijing to measure the ozone profile every week since 2001, and the collected data have been used to validate satellite measurements (Bian et al., 2007) and model products (Wang et al., 2012). The GPSO3 ozonesonde was developed based on the carbon-iodine ozone sensor type. This sensor consists of a single electrochemical cell containing a platinum gauze as the cathode and an activated carbon anode immersed in neutral potassium iodide solution (Wang et al., 2003). The anode electrode of the GPSO3 ozonesonde is made by sticking the carbon powder together. It has been shown that the air which may exist in the anode electrode can sometimes explode at low pressure levels and thus affect the ozone measurements; meanwhile, the ozone partial pressure measurements from the GPSO3 ozonesonde are higher than those from the ECC ozonesonde below 15 km and from 25 to 30 km (Zheng and Li, 2005).

The objective of the present paper is to describe the development of a double-cell ozonesonde at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), and report the results from an evaluation of its detection performance. Section 2 describes the instrumentation and the validation campaign. Comparisons among the measurements collected by the IAP ozonesonde, the ECC ozonesonde, the GPSO3 ozonesonde, and the Brewer ozone spectrophotometer, are presented in section 3. The main conclusions from the study are summarized in section 4.

2. Instrumentation and validation experiment

2.1. *Ozonesonde description*

The double-cell ozonesonde reported in the present paper was developed by the authors at the Key Laboratory of Middle Atmosphere and Global Environment Observation IAP/CAS. The ozonesonde is referred to as the "IAP ozonesonde" hereafter. Similar to the ECC type developed by Komhyr (1969), the IAP ozonesonde is based on an electrochemical method and consists of an anode cell and a cathode cell, as illustrated in Fig. 1. The physical dimensions of the ozonesonde are 76 mm in length, 72 mm in width, and 135 mm in height and the ozonesonde cell is made of Teflon. The cathode sensing solution of SST1.0% (1% KI and full buffer) described by Komhyr (1986) which is widely used for the ECC ozonesonde is also deployed by the IAP ozonesonde, and the chemical compositions are: KI (10 g L^{-1}); KBr (25 g L^{-1}); $NaH_2PO_4 \cdot H_2O$ (1.25 g L^{-1}); and $Na_2HPO_4 \cdot 12H_2O$ (5 g L^{-1}). A KI saturated water solution is employed for the anode sensing solution, and a platinum mesh is immersed in

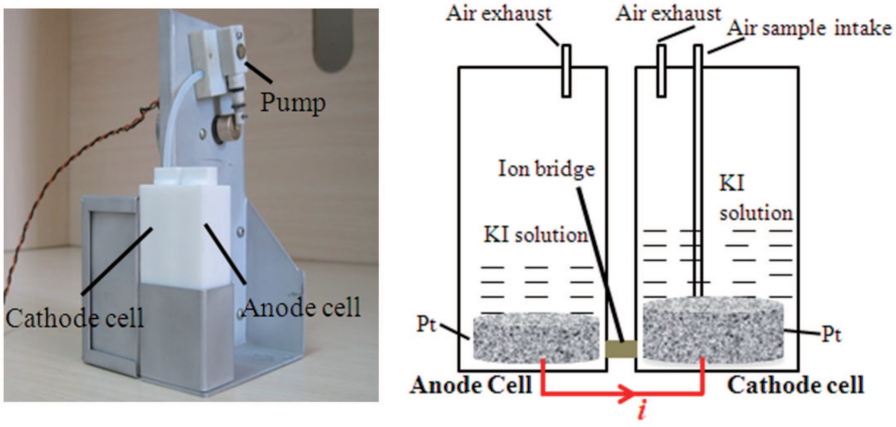

Fig. 1. Configuration of the IAP ozonesonde (left panel) and a schematic representation (right panel).

the solution to serve as electrodes in every cell. The iodometric method for measuring ozone is based on the fast reaction of ozone and iodide (I^-) producing iodine (I_2) in the cathode solution, which is represented by Eqs. (1) and (2):

$$2KI + O_3 + H_2O \rightarrow I_2 + O_2 + 2KOH\ , \quad (1)$$

$$I_2 + 2e \xrightarrow{Pt} 2I^-\ . \quad (2)$$

In the anode cell, there is a reaction as shown by Eq. (3)

$$2I^- - 2e \xrightarrow{Pt} I_2\ . \quad (3)$$

Two electrons are released by each ozone molecule in the equation. The air containing the ozone is bubbled through the cathode solution by a small electrically-driven gas sampling pump. The ozone partial pressure can be computed from the following equation:

$$P = 4.307 \times 10^{-4} \times (i - i_{BG}) \times T \times t \times (\eta \times \Phi_p)\ , \quad (4)$$

where P is the ozone partial pressure in millipascals (mPa); the constant 4.307 is determined by the half ratio of gas constant and Faraday constant (Komhyr, 1969); i is the cell output current in units of microamperes (μA); i_{BG} is the cell background current (in units of μA); T is the temperature of the ozonesonde box (in units of K); $t(s)$ is the time for the pump to bubble 100 milliliters of airflow through the cathode solution; η is the conversion efficiency, which includes the absorption efficiency of ozone into the sensing solution and the stoichiometry of the conversion of ozone into Iodine; and Φ_p is the efficiency of the pump flow rate. Note that the conversion efficiency (η) and the pump flow efficiency (Φ_p) were not tested during the campaign, and both of them were assumed to be one, or follow the correction coefficient presented by Science Pump Corporation (2010). The influences of these assumptions on the ozone measurements will be discussed in the validation analysis.

The aforementioned chemical reactions will slow down or even stop if excess anions are generated in the cathode cell and excess cations are produced in the anode cell. Therefore, to maintain the chemical reactions, the two chambers are linked by an ion bridge (Fig. 1b) which is used to provide an ion pathway and to prevent mixing of the electrolytes in the two cells. The ion bridge is the core component of the IAP ozonesonde, and stemmed from a large number of experiments ultimately resulting in the development and use of a special material designed for good performance.

The Standard Operating Procedures (SOPs) originally used for the ECC ozonesondes, which were achieved by the Assessment of Standard Operating Procedures for OzoneSondes (ASOPOS) panel in September 2004 at the WMO/ASOPOS meeting held in Juelich, Germany (Smit et al., 2013) were adopted to prepare the IAP ozonesonde. Based on these procedures, the amount of sensing solution used for the IAP ozonesonde is 3 mL for the cathode cell and 1.5 mL for the anode cell.

The IAP ozonesonde was prepared and tested three to seven days in advance of the launch. As part of this, two parameters—the background current and response time—were tested to evaluate the performance of the ozonesonde and this took place one hour after the injection of the solutions The sensing solutions were then replaced and the ozonesonde performance was tested again on the day of the flight.

2.2. *Validation experiment*

A total of 11 IAP ozonesondes were released from Beijing Observatory (number 54511; 39.81°N, 116.47°E; 31 m above sea level) from January to March 2013. The radiosonde used for data transmission during six of the launches was provided by the Changfeng Company, which participated in the Eighth WMO International Radiosonde Comparison held at Yangjiang, China, in 2010 (Nash et al., 2011); and the Vaisala RS92 radiosonde was deployed for the remaining five launches. In order to evaluate different ozonesondes' performances, the GPSO3, ECC and IAP ozonesondes were released together by the same balloon (Table 1). The launch time was around 14:00 Local Standard Time (LST). The balloon burst altitude was generally higher than 30 km, and the maximum was 35.0 km (Table 1).

For the first and second IAP ozonesonde launches in Table 1, a constant background current measured during preflight preparations at surface pressure was applied for the background current correction during the post-flight data

Table 1. Details of ozonesonde launches, weather conditions, and AOT during the launch time in the Beijing campaign.

	Launch day	Launch time (LST)	Burst altitude (km)	Weather conditions			AOT
				Cloud amount	Haze occurrence	Visibility (km)	
1	15 Jan.	1402:57	28.4	10	No	11.0	N.A.
2	22 Jan.	1358:18	31.3	3	Yes	1.5	N.A.
3*	11 Mar.	1348:29	30.4	8	No	15.0	2.11
4*	13 Mar.	1345:32	31.7	0	No	30.0	0.18
5*	14 Mar.	1351:11	33.7	10	No	20.0	1.31
6*	15 Mar.	1403:53	32.7	10	Yes	6.0	N.A.
7*	18 Mar.	1349:42	35.0	4	No	30.0	0.16

Note: N.A. means that AOT data were not available during the ozonesonde launch period; * denotes that both the ECC and IAP ozonesondes deployed Vaisala RS92 radiosondes for data transmission, and the pump correction coefficient presented by the Science Pump Corporation (2010) was applied to the two ozonesonde datasets.

processing throughout the entire ozone profile. No pump flow rate corrections were made for the first and second IAP ozonesonde launches. The correction coefficients for the background current and pump flow rate presented by the Science Pump Corporation (2010) and originally used for the Model SPC-6A ECC ozonesonde were tentatively applied to the third to seventh IAP ozonesonde launches, with the aim of testing the applicability of these correction coefficients for the IAP ozonesonde As shown by the results presented in section 3, the Science Pump Corporation flow rate correction coefficients are not quite suitable for the IAP ozonesonde and thus we need to derive new ones in a future study.

The ECC ozonesonde type employed in this study was the ENSCI-Z whose manufacturer is ENSCI-Corporation. The ENSCI-Z ozonesondes were launched together with the Vaisala RS92–SGP radiosonde. The aforementioned SOPs were also applied during the ENSCI-Z ozonesonde preparation procedures. The cathode sensing solution used for the ENSCI-Z ozonesonde was SST0.5% (0.5% KI and half buffer) which was composed of: KI (5 g L^{-1}); KBr (12.5 g L^{-1}); $NaH_2PO_4{\cdot}H_2O$ (0.625 g L^{-1}); and $Na_2HPO_4{\cdot}12H_2O$ (2.5 g L^{-1}). A KI saturated cathode solution was employed for the anode sensing solution. The amount was 3 mL for the cathode sensing solutions and 1.5 mL for the anode sensing solutions. The corrections for the background current and pump flow rate presented by the SOPs were made for the ENSCI-Z ozonesonde.

The ground check parameters, i.e. background current, response time, and pump flow velocity, obtained on the day of the flight for the IAP and ECC ozonesondes detailed in Table 1 are shown in Table 2. In general, they were generally less than 0.05 μA, around 30 s, and around 30 s respectively for the IAP ozonesonde, which were close to the values of the ECC ozonesonde.

Total ozone concentration measurements derived from a Brewer ozone spectrophotometer (#197), located in the northwest about 20 km away from the campaign field, were employed to validate the ozonesonde measurements. Furthermore, the average aerosol optical thickness (AOT) measurements obtained from the Aerosol Robotic Network of the sun photometer (AERONET) (Holben et al., 1998), with more than one sample collected during each ozonesonde launch period at the Beijing site (39.98°N, 116.38°E; 92 m above sea level), was used to investigate the effect of haze on the agreement of the ozone measurements between the Brewer and ozonesonde instruments. In addition, ground-based manual observations, including cloud amount, haze occurrence, and visibility, were collected over the campaign field, and the data are shown in Table 1.

The ECC data presented in this paper are comparable in terms of quality and robustness to the results obtained in the JOSIE and BESOS validation campaigns for two reasons. Firstly, all the ECC ozonesonde operating procedures, including the pre-flight preparation, launch, and post-flight data processing, were conducted by strictly observing the aforementioned SOPs. Secondly, as shown by the results presented in section 3, the level of agreement between the total ozone column measurements collected by the ECC ozonesonde and the Brewer instrument was quite high. The Brewer measurements used in this study were from MKIII#197, which participated in the intercomparison campaign of the international traveling standard Brewer #017 in 2012. This proved that its relative and absolute bias of total ozone column collections is less than 1% and 2.5 Dobson Units (DU) for each sample. In view of this high observational accuracy, the Brewer instrument used in this study was employed as the transfer standard to the other Brewer instruments deployed by the China Meteorology Administration.

Table 2. The background current (μA), response time (s), and pump flow velocity (s) obtained on the day of the flight for the IAP and ECC ozonesondes.

	IAP (ECC) ozonesonde		
	Background current	Response time	Pump flow velocity
1	0.03 (0.01)	29.64 (28.60)	27.5 (29.6)
2	0.03 (0.18)	27.24 (27.52)	28.0 (28.9)
3	0.01 (0.01)	32.42 (29.66)	29.5 (29.1)
4	0.03 (0.01)	31.02 (32.61)	29.5 (26.8)
5	0.03 (0.01)	31.40 (32.30)	29.0 (27.0)
6	0.02 (0.01)	34.78 (32.82)	29.9 (26.3)
7	0.01 (0.02)	30.21 (27.36)	28.5 (29.1)

3. Results and discussion

3.1. *Comparisons of ozone measurements from different ozonesondes*

Figure 2 shows a case of ozone profile comparison between the IAP and GPSO3 ozonesondes launched on January 8, 2013 at 1439 LST. The GPSO3 ozonesonde was able to capture the ozone pattern detected by the IAP ozonesonde at high air pressure levels; however, as mentioned in section 1, instrument breakdown tends to occur in the GPSO3 ozonesonde at low air pressure levels (Fig. 2a), which was also revealed in some other launches during the Beijing campaign. The absolute difference in ozone measurements from the two sets of ozonesondes was generally less than 2 mPa below 25 km (Fig. 2b). Higher ozone partial pressure tended to be measured by the GPSO3 ozonesonde below 15 km, which was consistent with the study of Zheng and Li (2005). The GPSO3 ozonesonde has been launching for over 10 years at the Beijing site; but as shown by the present analysis, as well as results presented by Zheng and Li (2005), the data measured by the GPSO3 ozonesonde over the past decade will need further evaluation, and the consistency between its measurements and those of the IAP ozonesonde should be taken into careful consideration in the future.

The vertical ozone distributions measured by the IAP and ECC ozonesondes from the second launch are shown in Fig. 3. In general, the IAP ozonesonde was able to capture the vertical ozone structures very well, and there was good agreement between the ozone concentrations measured by the IAP and ECC ozonesondes (Fig. 3a). More specif-

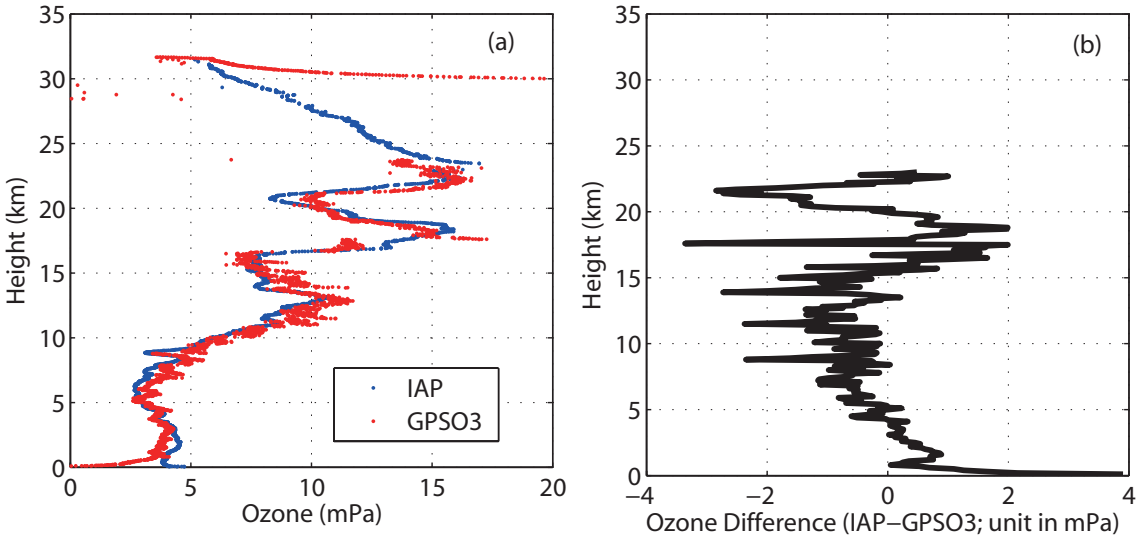

Fig. 2. Comparison of ozone amounts observed by the IAP (blue dots) and GPSO3 (red dots) ozonesondes (a) and their differences (b).

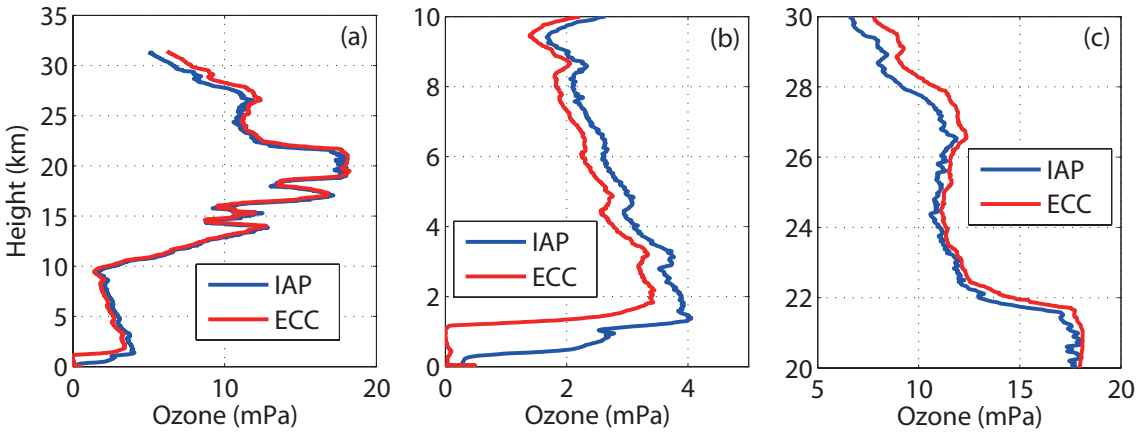

Fig. 3. The vertical ozone distributions obtained from the second launch with the IAP and ECC ozonesondes released together. Panels (a–c) show measurements collected at all altitude ranges, lower than 10 km, and from 20 to 30 km, respectively.

ically, relatively larger differences occurred at layers lower than 2.5 km and higher than 27 km, as compared with layers between 2.5 and 27 km. Figures 3b and 3c show the zooming in plots for levels lower than 10 km and levels ranging from 20 to 30 km. For layers less than 10 km (Fig. 3b), the IAP ozonesonde measurements were systematically larger than the ECC ozonesonde measurements by 0.5–2.5 mPa. Note that the ECC detections were close to 0 mPa from the surface to 1.2 km, which is obviously unreasonable. On the contrary, the IAP measurements ranged from 0.2 to 2.5 mPa, which is acceptable. A haze characterized by extraordinary low visibility (1.5 km) occurred during the ozonesonde launch period (Table 1). It has been suggested that pollutant gases, such as SO_2 and NO_x, can affect ozonesonde measurements near the surface or even upwards to several kilometers above the ground level (Schenkel and Broder, 1982). The measurements from the IAP ozonesonde were generally larger than the ECC ozonesonde at low-level altitude, which may be due to the ECC ozonesonde accumulating more pollution than the IAP ozonesonde associated with the longer running time for the ECC ozonesonde during the pre-flight preparation procedures. The IAP ozonesonde detected less ozone amounts than the ECC ozonesonde from 20 km to 30 km (Fig. 3c), and these discrepancies were probably caused by a decreasing pump flow rate in the IAP ozonesonde. The pump volumetric flow rate is relatively constant from surface pressure to about 300 hPa during the balloon flight; however, one would expect a steady decrease in the pump flow rate with altitude higher than 300 hPa due to an increase in resistance from pumping against the cathode solution fluid head, dead space in the cylinder of the piston pump, and pump leakage (Komhyr et al., 1995; Steinbrecht et al., 1998; Johnson et al., 2002). The

pump flow rate coefficient for the IAP ozonesonde was assumed to be one at all levels for this launch, which likely resulted in the lower ozone measurements by the ozonesonde.

Figures 4a–f show comparisons of vertical ozone distributions obtained from the ECC and IAP ozonesondes from the remaining six launches in Table 1. Similar to Fig. 3, the IAP ozonesonde was able to capture the vertical ozone patterns reasonably well, reflecting the features seen in the ECC measurements in Fig. 4. Good agreement can be seen in the first, third, and fourth panels. The pump correction coefficient presented by the Science Pump Corporation (2010) was applied to the measurements obtained by both the ECC and IAP ozonesondes presented in the second to sixth panels. Nevertheless, relatively large discrepancies can still be seen in the second, fifth, and sixth panels, in which the IAP ozonesonde measurements are shown to have been smaller than the ECC measurements by < 3 mPa above 20 km due to the decreasing pumping rate in the IAP ozonesonde. There should be a difference in pump flow behavior at low pressures between the IAP and ECC ozonesondes due to the different manufacturing materials and processes deployed by the two sets of ozonesondes Therefore, further studies are needed to derive a suitable pump correction factor as a function of altitude for the IAP ozonesonde.

The vertical differences between the ozone measurements from the IAP and ECC ozonesondes for all launches are shown in Fig. 5a. In the lower atmosphere, the IAP ozonesonde detections were usually larger than those obtained from the ECC ozonesonde, with the maximum difference being ~ 3 mPa at a few levels in the second and third launches. As mentioned above, the haze occurred during the second ozonesonde launch period (Table 1); meanwhile, the AOT was very large (2.11) during the third launch. So, the polluted air may have deteriorated the ECC detections at low-altitude levels. In the upper atmosphere, the IAP ozonesondes generally detected less ozone than the ECC ozonesonde, and the difference was close to -2 mPa at levels from 15 km to 30 km for the sixth and seventh launches. Figure 5b illustrates the average ozone distributions obtained by the two instruments. In general, the measurements from the IAP and ECC ozonesondes agreed well, except that a slight ozone deficiency was apparent in the IAP ozonesonde measurements in the upper atmosphere. Figure 5c shows the average difference in vertical ozone measurements between the two types of ozonesondes and their standard deviation. The average difference was less than 0.3 mPa from the surface up to 2.5 km, and then decreased to close to zero. The difference remained stable to 9 km, and then began to decrease obviously up to 22 km (about -1 mPa). The standard deviation of the ozone difference was generally less than 1 mPa.

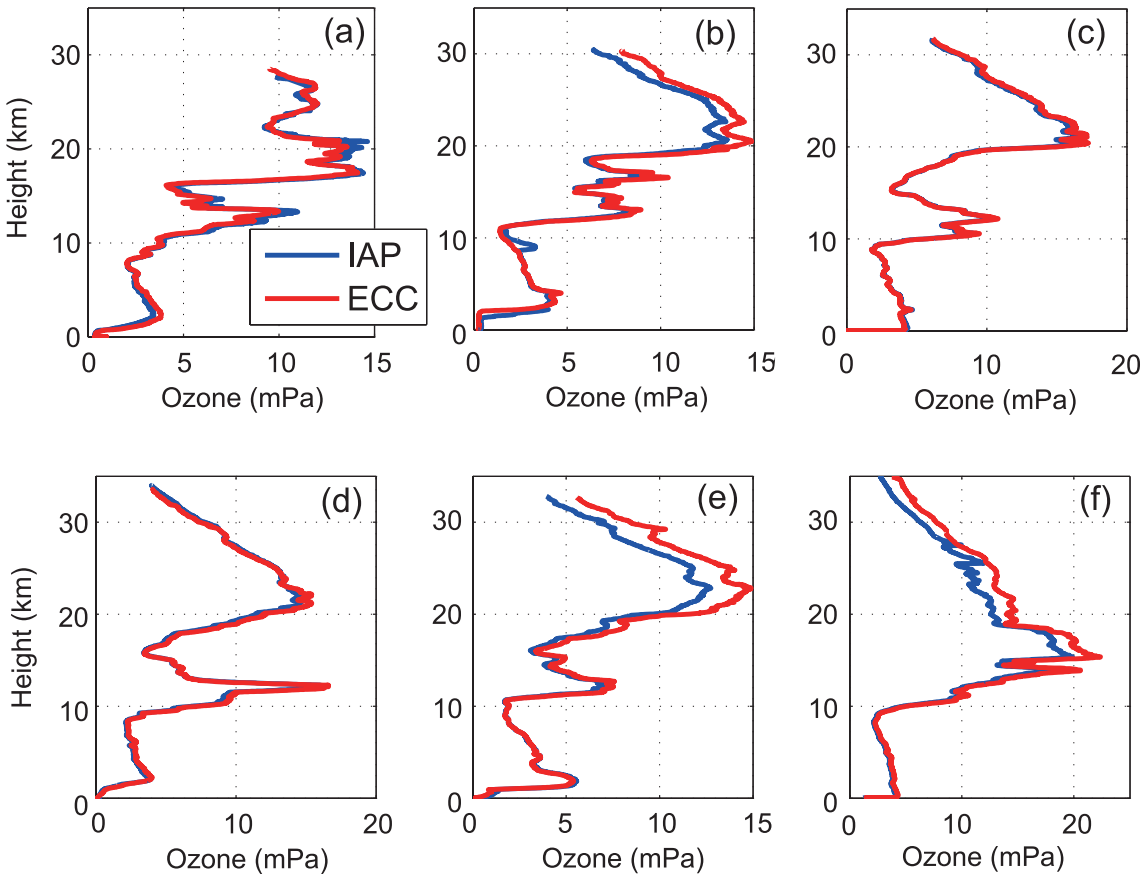

Fig. 4. (a–f) Vertical ozone distributions obtained from the first, third, fourth, fifth, sixth, and seventh launches (Table 1) with the IAP and ECC ozonesondes released together.

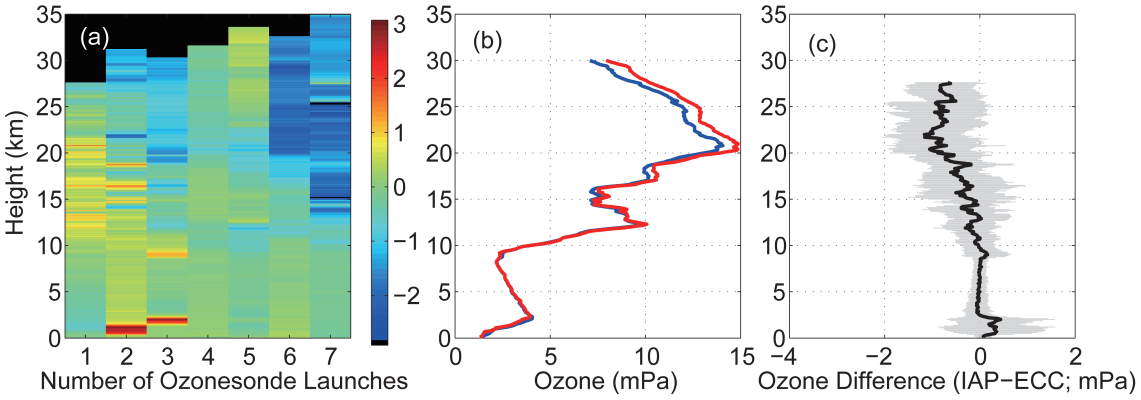

Fig. 5. (a) Difference in vertical ozone measurements between the IAP and ECC ozonesondes (IAP minus ECC) for the seven launch cases detailed in Table 1. The areas colored in black denote the altitude ranges without detections, and the other colors represent the ozone differences. (b) Comparisons of average vertical ozone structures derived from the IAP (blue line) and ECC ozonesonde (red line) measurements. (c) Average difference of vertical ozone measurements from the two types of ozonesonde and their standard deviation.

3.2. *Comparison of ozonesonde- and Brewer-derived total ozone column*

A comparison of the integrated ozone columns of the IAP and ECC ozonesondes up to balloon burst altitude is shown in Fig 6. The average relative difference and correlation coefficient were 53% and 0.96 for the two sets of ozonesonde data. In general, the level of agreement between the measurements from the two types of ozonesonde was reasonably high, except that the IAP ozonesonde retrievals were slightly less than those from the ECC ozonesonde.

The total ozone column from the ozonesonde consists of the integrated column of the ozonesonde profile plus a climatology of residual ozone column data above the balloon burst altitude derived from satellite observations (McPeters et al., 1997). A comparison of the total ozone column from ozonesonde measurements and that derived from the Brewer ozone spectrophotometer (#197) is shown in Fig. 7. The blue dots represent the IAP ozonesondes launched alone (IAP1); pink dots represent the IAP ozonesondes (IAP2) and red squares represent the ECC ozonesondes flown together (Fig. 7a). In general, the ozonesonde-based retrievals produced smaller measurements than the Brewer instrument, and this was more obvious for the IAP ozonesonde. The relative difference (defined as the difference between retrievals from the Brewer instrument and the ozonesonde, divided by the Brewer measurements) and correlation coefficient for all launches in Table 1 were 1.8% and 0.98 for ECC ozonesonde and Brewer, and 6% and 0.94 for IAP ozonesonde and Brewer; thus, the Brewer instrument detected larger ozone amounts than the two types of ozonesonde. Large differences between the measurements derived from the ECC ozonesonde and the Brewer instrument occurred during the second, third and fifth launches detailed in Table 1. However, the ECC and IAP measurements were generally in close agreement. Good agreement was also seen between the ECC ozonesonde and Brewer column-integrated concentrations obtained during the remaining four launches. A few heavy haze events occurred during the experimental period in Beijing, such as during the second launch (Table 1). The average AOT at 440 nm was 0.67 from January to March 2013. Table 1 presents the available AERONET AOTs for the third, fourth, fifth and seventh launches. There were no enough observational AOT data corresponding to the first, second, and sixth launches due to the occurrence of cloud, rain, and snow. Figure 7 and Table 1 show that the cases where the large differences existed in total ozone measurements between the ozonesondes and Brewer instrument (third and fifth launches) corresponded to conditions under which AOT was relatively large. Good agreement occurred (fourth and seventh launches) when a relatively small AOT was observed. The lack of observational data prevents us from sufficiently investigating the influence of haze on the agreement between ozonesonde- and Brewer-derived measurements; but, we can speculate that the heavy haze and its transport might have induced the discrepancies between the two datasets.

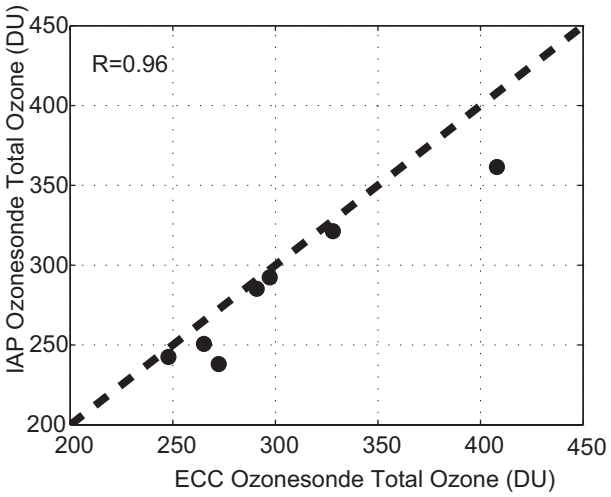

Fig. 6. Comparison of integrated ozone columns of the IAP and ECC ozonesondes up to balloon burst altitude.

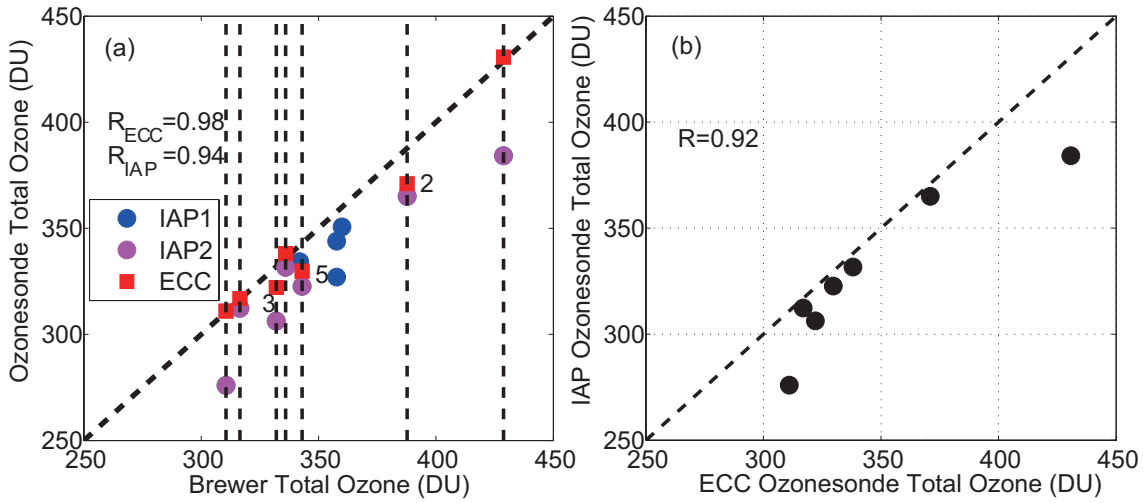

Fig. 7. (a) Comparison of the total ozone column derived from measurements by ozonesondes and the ground-based Brewer ozone spectrophotometer. The blue dots represent the IAP ozonesondes launched alone (IAP1); pink dots represent the IAP ozonesondes (IAP2) and red squares represent the ECC ozonesondes flown together. The thick black dashed line denotes the 1:1 line; and the black thin dashed line connects the IAP and ECC ozonesondes released together. The numbers 2, 3 and 5 represent the ozonesonde launch numbers detailed in Table 1. (b) Comparison of total ozone column retrieval from the two sets of ozonesonde data.

Figure 7b shows a comparison between the total ozone column derived from the two types of ozonesondes. The relative difference and correlation coefficient were 4.9% and 0.92 for the two sets of ozonesonde data. As we can see, the level of agreement was very good for four ozonesonde launches in which the relative difference and correlation coefficient were 1.8% and ~ 1.0, respectively. The relatively large deficiency in the other three launch cases was also likely caused by the low pump flow rate coefficient in the upper atmosphere, lending more weight to the need for us to enhance the consistency of the Chinese-made pumps, as well as derive a suitable pump correction factor as a function of altitude for the IAP ozonesonde. The comparisons of total ozone column among the IAP ozonesonde, ECC ozonesonde, and Brewer spectrophotometer for the seven launches detailed in Table 1 are summarized in Table 3.

Table 3. Comparison of total ozone column derived from the IAP ozonesonde, ECC ozonesonde, and Brewer spectrophotometer for the seven launch cases with two types of ozonesonde launched together.

	(Brewer-IAP)/ Brewer	(Brewer-ECC)/ Brewer	(ECC-IAP)/ ECC
Minimum difference	1.3%	0.1%	1.4%
Maximum difference	11.1%	4.5%	11.2%
Average difference	6.0%	1.8%	4.9%
Correlation coefficient	0.94	0.98	0.92

4. Summary and conclusion

The single-cell GPSO3 ozonesonde has been developed and deployed in China for over two decades. Compared to single-cell ozonesonde technology, ozonesondes formed by two half cells demonstrate more technical advantages. To collect more reliable observational data, a double-cell ozonesonde has been developed at the IAP/CAS and is expected to replace the GPSO3 ozonesonde in the near future in China. Details of the IAP ozonesonde have been presented in the current paper, along with results from a series of launches carried out to evaluate its reliability and accuracy.

A total of 11 IAP ozonesondes were released in Beijing from January to March 2013, of which seven were lunched together with ECC ozonesondes by the same balloon. The results showed that, in general, the IAP ozonesonde is able to successfully capture vertical ozone structures, as indicated by the good level of agreement between its measurements and those of the ECC ozonesonde. Their average difference was about 0.3 mPa from the surface to 2.5 km, then decreased to close to zero and remained stable up to 9 km. The relative difference and correlation coefficient were 6% and 0.94 for the total ozone column from the IAP ozonesonde and Brewer instrument, and 4.9% and 0.92 for the two sets of ozonesonde data. The Brewer instrument tended to detect larger ozone amounts than the ozonesondes. It demonstrated that the difference in total ozone column between the ozonesonde and the Brewer instrument, as well as the difference of measurements at low altitude levels between IAP and ECC ozonesondes could be partly blamed on the regional air pollution and heavy haze over the campaign field. However, the deficiencies in ozone measurements form the IAP ozonesonde were mainly caused by a decrease in the pump flow rate in the upper atmosphere.

The results presented in this study have proven that the IAP ozonesonde can successfully capture vertical ozone distributions, and with higher detection accuracy than the

GPSO3 ozonesonde. This advancement will surely accelerate the process of conventional IAP ozonesonde observations over the large territory of China, and thus provide more data sources for ozone research in general. In the next stage of our work, we will endeavor to solve a number of problems. Firstly, we will attempt to derive a suitable pump correction factor as a function of altitude for the IAP ozonesonde. Secondly, the effect of air pollution and haze on ozonesonde measurements will be quantitatively acquired by more investigations conducted in simulated conditions and the real atmosphere. And finally, the GPSO3 data collected in the past will be comprehensively checked and corrected to ensure consistency among measurements after moving from the GPSO3 ozonesonde to the IAP ozonesonde.

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REFERENCES

Bian, J. C., A. Gettelman, H. B. Chen, and L. Pan, 2007: Validation of satellite ozone profile retrievals using Beijing ozonesonde data. *J. Geophys. Res.*, **112**, D06305, doi: 10.1029/2006JD007502.

Brewer, A. W., and J. R. Milford, 1960: The Oxford Kew ozonesonde. *Proceedings of the Roy Society London, Series A*, **256**, 470–495.

Deshler, T., and Coauthors, 2008: Atmospheric comparison of electrochemical cell ozonesondes from different manufacturers, and with different cathode solution strengths: The Balloon Experiment on Standards for Ozonesondes. *J. Geophys. Res.*, **113**, D04307, doi: 10.1029/2007JD008975.

Farman, J. D., B. G. Gardiner, and J. D. Shanklin, 1985: Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature*, **315**, 207–210.

Johnson, B. J., S. J. Oltmans, H. Vömel, H. G. J. Smit, T. Deshler, and C. Kroger, 2002: Electrochemical concentration cell (ECC) ozonesonde pump efficiency measurements and tests on the sensitivity to ozone of buffered and unbuffered ECC sensor cathode solutions. *J. Geophys. Res.*, **107**(D19), ACH8-1–ACH8-18, doi: 10.1029/2001JD000557.

Holben, B. N., and Coauthors, 1998: A federated instrument network and data archive for aerosol characterization. *Remote Sens. Environ.*, **66**, 1–16, doi: 10.1016/S0034-4257(98)00031-5.

Kobayashi, J., and Y. Toyama, 1966: On various methods of measuring the vertical distribution of atmospheric ozone (III)—Carbon iodine type chemical ozone sonde. *Pap. Meteor. Geophys.*, **17**, 113–126.

Komhyr, W. D., 1969: Electrochemical concentration cells for gas analysis. *Ann. Geophys.*, **25**, 203–210.

Komhyr, W. D., 1986: Operations handbook-Ozone measurements to 40 km altitude with model 4A-ECC-ozone sondes. NOAA Tech Memorandum ERL-ARL-149.

Komhyr, W. D., R. A. Barnes, G. B. Brothers, J. A. Lathrop, and D. P. Opperman, 1995: Electrochemical concentration cell ozonesonde performance evaluation during STOIC 1989. *J. Geophys. Res.*, **100**, 9231–9244.

Logan, J A, 1999: An analysis of ozonesonde data for the troposphere: Recommendations for testing 3-D models and development of a gridded climatology for tropospheric ozone. *J. Geophys. Res.*, **104** 16 115–16 149.

McPeters, R. D., G. J. Labow, and B. J. Johnson, 1997: A satellite-derived ozone climatology for balloonsonde estimation of total column ozone. *J. Geophys. Res.*, **102**, 8875–8885.

Nash, J., T. Oakley, H. Vömel, and W. Li, 2011: WMO intercomparison of high quality radiosonde systems Yangjiang, China, 12 July–3 August 2010. WMO/TD-No. 1580.

Science Pump Corporation, 2010: Operator's Manual Model 6A ECC Ozonesonde. [Available online at http://www.docstoc.com / docs / 24322231 / SCIENCE- PUMP-CORPORATION-OPERATORS-MANUAL-MODEL-6A-ECC-OZONESONDE].

Schenkel, A., and B. Broder, 1982: Interference of some trace gases with ozone measurements by the KI method. *Atmos. Environ.*, **16**, 2187–2190.

Smit, H. G. J., and D. Kley, 1998: The 1996 WMO International intercomparison of ozonesondes under quasi flight conditions in the environmental simulation chamber at Jülich. WMO Global Atmos. Watch Rep., 130, World Meteorol. Organ., Geneva, Switzerland, 108 pp.

Smit, H. G. J., and W. Sträter, 2004a: The 2000 WMO international intercomparison of operating procedures for ECC-ozone sondes at the environmental simulation facility at Jülich. WMO Global Atmos. Watch Rep., No. 158, World Meteorol. Organ., Geneva, Switzerland, 146 pp.

Smit, H. G. J., and W. Sträter, 2004b: JOSIE-1998 performance of ECC ozone sondes of SPC-6A and ENSCI-Z type. WMO Global Atmos. Watch Rep., No. 157, World Meteorol. Organ., Geneva, Switzerland, 64 pp.

Smit, H. G. J., and Coauthors, 2007: Assessment of the performance of ECC-ozonesondes under quasi-flight conditions in the environmental simulation chamber: Insights from the Juelich Ozone Sonde Intercomparison Experiment (JOSIE). *J. Geophys. Res.*, **112**, D19306, doi: 10.1029/2006JD007308.

Smit, H. G. J., and Coauthors, 2013: Quality Assurance and Quality Control for Ozonesonde Measurements in GAW. WMO Global Atmos. Watch Rep., 201, World Meteorol. Organ., Geneva, Switzerland, 92 pp.

Steinbrecht, W., R. Schwartz, and H. Claude, 1998: New pump correction for the Brewer-Mast ozone sonde: Determination from experiment and instrument intercomparisons. *J. Atmos. Ocean. Technol.*, **15**, 144–156.

Stübi, R., G. Levrat, B. Hoegger, P. Viatte, J. Staehelin, and F. J. Schmidlin, 2008: In-flight comparison of brewer-mast and electrochemical concentration cell ozonesondes. *J. Geophys. Res.*, **113**, D13302, doi: 10.1029/2007JD009091.

Thompson, A. M., and Coauthors, 2003: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998–2000 tropical

ozone climatology: 1. Comparison with Total Ozone Mapping Spectrometer (TOMS) and ground-based measurements. *J. Geophys. Res.*, **108**(D2), 8238, doi: 10.1029/2001JD000967.

Thompson, A. M., and Coauthors, 2007: Intercontinental chemical transport experiment ozonesonde network study (IONS) 2004: 2. Tropospheric ozone budgets and variability over northeastern North America. *J. Geophys. Res.*, **112**, D12S13, doi: 10.1029/2006JD007670.

Thompson, A. M., S. J. Oltmans, D. W. Tarasick, P. von der Gathen, H. G. J. Smit, and J. C. Witte, 2011: Strategic ozone sounding networks: Review of design and accomplishments. *Atmos. Environ.*, **45**, 2145–2163.

Vömel, H., and K. Diaz, 2010: Ozone Sonde cell current measurements and implications for observations of near-zero ozone concentrations in the tropical upper troposphere. *Atmospheric Measurement Techniques*, **3**(2), 495–505, doi: 10.5194/amt-3-495-2010.

Wang, G. C., Q. X. Kong, Y. J. Xuan, X. W. Wan, H. B. Chen, and S. Q. Ma, 2003: Development and application of ozonesonde system in China. *Advance in Earth Sciences*, **18**(3), 471–475. (in Chinese with English abstract)

Wang, Y., and Coauthors, 2012: Tropospheric ozone trend over Beijing from 2002-2010: ozonesonde measurements and modeling analysis. *Atmos. Chem. Phys.*, **12**, 8389–8399, doi: 10.5194/acp-12-8389-2012.

Xuan, Y. J., S. Q. Ma, H. B. Chen, G. C. Wang, Q. X. Kong, Q. Zhao, and X. W. Wan, 2004: Intercomparisons of GPSO3 and Vaisala ECC ozone sondes. *Plateau Meteorology*, **23**(3), 394–399. (in Chinese with English abstract)

Zheng, X. D, and W. Li, 2005: Analysis of the data quality observed by the Chinese-made ozone sonde system. *Quart J Appl Meteor.*, **16**(5), 608–618. (in Chinese with English abstract)

Zhou, X. J., and C. Luo, 1994: Ozone valley over Tibetan Plateau. *Acta Meteorologica Sinica*, **8**(4), 505–506.