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An Empirical Model for Estimating Stratospheric Ozone Vertical Distributions over China

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ABSTRACT

Based on the Stratospheric Aerosol and Gas Experiment (SAGE) II and the Halogen Occultation Experiment (HALOE) ozone profiles and the Total Ozone Mapping Spectrometer (TOMS) total ozone data sets, an empirical model for estimating the vertical distribution of stratospheric ozone over China is proposed. By using this model, the vertical distribution of stratospheric (16–50 km) ozone can be estimated according to latitude, month and total ozone. Comparisons are made between the modeled ozone profiles and the SAGEII/HALOE monthly mean ozone measurements, and the results show that the model calculated ozone concentrations conform well with the SAGEII/HALOE measured values, with the differences being less than 15% between 16 km and 18 km, less than 5% between 19 km and 40 km, and less than 10% between 41 km and 50 km. Comparisons of the model results with balloon-borne ozonesonde measurements performed in Beijing also show good agreement, within 5%, at altitudes between 19 km and 30 km.

Key words: ozone, vertical distribution, empirical model

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1. Introduction

The vertical distribution of ozone patterns plays an important role in the earth's radiation budget and climate change (Wang et al., 1980; Shi, 1992). In order to establish a climate model and a radiation forcing model, knowledge of the vertical structure of an ozone parameter is needed. Keating and Young (1985) and Keating et al. (1987, 1996) have developed a reference model of the vertical distributions of ozone for the latitudes between 80°S–80°N, based on different satellite data sets. Wang et al. (1999) have updated Keating's reference model on the basis of SAGEII, HALOE, and the Microwave Limb Sounder (MLS) satellite data records. These models have been used for many practical purposes (McDermid et al., 1990). China is located in the eastern part of Eurasia and the vertical distribution pattern of ozone has its own characteristics in comparison with other regions of the same latitude. In this study, we have produced a parameterized empirical model simulating the stratospheric vertical distribution of ozone over China on the basis of the long-term satellite ozone data sets.

The SAGEII and HALOE instruments employ the solar occultation technique for measuring the profile of ozone concentration at sunrise and sunset (Mauldin et al., 1985; McCormick, 1987; Chu et al., 1989; Russell et al., 1993). The technique provides good vertical resolution and very small long-term drift resulting from instrument calibration, but spatial sampling is limited. Detailed intercomparisons of SAGEII/HALOE and other measurements had been preformed by many authors (Harris et al., 1998; Bhatt et al., 1999; Morris et al., 2002; Nazaryan et al., 2005; Nazaryan and McCormick, 2005), and the comparison results demonstrated that the SAGEII and HALOE data sets are reliable and accurate above the 100 hPa (about 16 km) level, especially over the altitudes of 20 to 50 km. In this study, we combine the SAGEII and HALOE vertical distribution data sets of ozone, and TOMS total ozone data records to derive an empirical model for estimating the stratospheric ozone profile concentra-

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tions.

2. Data and method

In this study, the SAGEII (version 6.2) and HALOE (version 19) vertical distribution data sets of ozone, and TOMS (version 8) total ozone data sets from March 1997 to February 2002 are used to derive monthly mean vertical distributions of ozone and total ozone values for different latitude bands of China.

In order to analyze the ozone distribution patterns of different parts of China, we used four latitude bands for this study: 50°±5°N, 40°±5°N, 30°±5°N, 20°±5°N, with the longitude range 75°–135°E, which include the main parts of China and some neighboring countries.

In our study, monthly means of SAGEII/HALOE ozone profiles and the correlated monthly mean TOMS total ozone values were calculated for each latitude band in the period from March 1997 to February 2002. Considering that the SAGEII/HALOE ozone profile data sets are limited during the summertime at the latitude bands of 30°±5°N and 20°±5°N, we used the SAGEII/HALOE and TOMS data sets for June, July, and August from 1997 to 2004 to calculate the monthly mean ozone in June, July, and August for these two latitude bands.

3. An empirical model for estimating stratospheric ozone profiles over China

In this section, we describe a parameterized empirical model for estimating the average stratospheric ozone profiles over China on the basis of the monthly mean SAGEII/HALOE ozone profiles and TOMS total ozone records for different latitude bands of 50° ±5°N, 40° ±5°N, 30° ±5°N, and 20° ±5°N. Although there are significant local-time variations in the vertical distribution of ozone, the long-term averaged ozone profiles have regular features, which are mainly correlated with latitude, month and total ozone. In order to describe the vertical distribution of ozone features in the stratosphere, we analyzed the ozone concentration data at different altitude levels and their relations with the latitude, month and total ozone.

The monthly averaged vertical distribution patterns of ozone show that in the altitudes between 20 km and 28 km, the vertical distribution of ozone is correlated with latitude, month and total ozone. In the altitudes between 29 km and 42 km, the ozone distribution is largely determined by photochemical reaction effects, and its distribution is determined by the latitude and month. At the altitudes above 42 km, the ozone distribution approximately presents an exponential profile, with relatively small variations. Below 20 km, the ozone distribution is largely determined by dynamics and transport and undergoes a dramatic variation. Since there are significant differences between the SAGEII and HALOE measurements below 16 km altitude, we used the vertical distribution of ozone data from 16–50 km for analyses.

Wang et al. (1985) has introduced an empirical expression proposed by Vigroux (1963) in his book. To determine the vertical distribution of ozone from the tropopause to 26 km, the Vigroux's expression is given by:

$$\rho_{O_3} = A(Z-c)^m \exp(-nZ)\,, \qquad (1)$$

where A, m, and n are the empirical coefficients; $c = H_T - 2.5$, and H_T is the altitude of the tropopause.

In Vigroux's empirical expression, the effect of the total ozone is not considered. In actuality, ozone concentrations in the lower stratosphere are largely correlated with the total ozone values. In this paper, we improved this expression by adding a term related to the total ozone. According to the average ozone profile characteristics in different latitude bands of China, we derived a parameterized empirical model for estimating the vertical distribution of stratospheric ozone.

In the altitudes between 16 km and 28 km, the vertical distribution of ozone is of the form:

$$\rho_{O_3} = a_0(Z-c_0)^{a_1}\exp(-c_1 Z) + 0.06\left(100\frac{X-X_0}{X_0}\right)^3 \exp[-(Z-c_2)^2/32.0]\,, \qquad (2)$$

where ρ_{O_3} is the ozone density with the units of μg cm^{-3}, Z is the altitude in kilometers (km); X is the actual total column of ozone with the unit of DU (Dobson Unit); X_0 is the average monthly mean of the total column of ozone with the unit of DU; a_0 and a_1 are the empirical coefficients related to the latitude and the month; c_0, c_1, and c_2 are the empirical coefficients related to the latitude; In the latitude bands 50°±5°N, 40°±5°N, 30°±5°N, and 20°±5°N, c_0 values are 8.0, 9.0, 10.0, and 11.0 km respectively; c_1 values are 0.3, 0.36, 0.5 and 0.5 respectively, and c_2 values are 17.0, 17.0, 23.0, and 26.0 km respectively. In Eq. (2), the first term represents the vertical concentrations of ozone when the total ozone X equals X_0; the second term gives the differences in the vertical distribution of ozone values when $X \neq X_0$.

In the altitudes between 29 km and 42 km, the vertical distribution of ozone is of the form:

$$\rho_{O_3} = 66.0\exp[-b(Z-42.0)] - 40.0\,, \qquad (3)$$

where b is the empirical coefficient related to the latitude and the month.

Table 1. Empirical coefficients for each month in the 50°±5°N latitude band.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
X_0	380	380	400	380	360	340	310	300	300	300	320	350
a_0	40.0	52.0	41.0	14.7	4.20	2.28	1.70	0.96	1.48	6.36	9.30	16.6
a_1	3.40	3.30	3.40	3.75	4.20	4.40	4.50	4.70	4.55	4.00	3.90	3.70
b	0.098	0.100	0.106	0.109	0.114	0.114	0.114	0.114	0.114	0.104	0.103	0.101

Table 2. Same as Table 1, but for the latitude band of 40°±5°N.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
X_0	330	330	350	340	330	310	290	290	290	290	300	310
a_0	17.7	17.2	11.0	4.72	0.69	0.69	0.28	0.28	0.51	1.50	2.70	8.00
a_1	4.32	4.32	4.50	4.80	5.50	5.50	5.80	5.80	5.60	5.20	5.00	4.60
b	0.101	0.103	0.110	0.114	0.122	0.122	0.122	0.122	0.122	0.114	0.112	0.104

Table 3. Same as Table 1, but for the latitude band of 30°±5°N.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
X_0	270	270	280	290	290	290	280	270	270	260	260	260
a_0	1.06	1.06	0.74	0.44	0.152	0.152	0.152	0.087	0.087	0.146	0.24	0.54
a_1	6.75	6.75	6.90	7.10	7.50	7.50	7.50	7.70	7.70	7.50	7.30	7.00
b	0.108	0.110	0.116	0.120	0.126	0.126	0.126	0.126	0.126	0.120	0.116	0.110

Table 4. Same as Table 1, but for the latitude band of 20°±5°N.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
X_0	240	240	260	280	280	280	280	280	280	260	240	240
a_0	0.43	0.44	0.47	0.49	0.52	0.50	0.50	0.50	0.50	0.48	0.46	0.43
a_1	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25
b	0.116	0.121	0.124	0.128	0.130	0.130	0.130	0.130	0.130	0.127	0.121	0.117

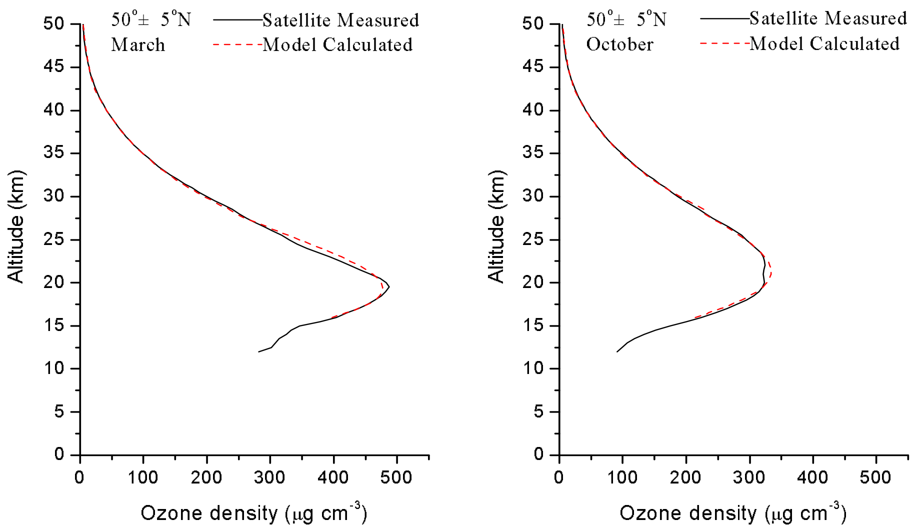

Fig. 1. Comparisons of the model calculated and the SAGEII/HALOE satellite measured monthly mean ozone profiles of March and October for the latitude band of 50°±5°N.

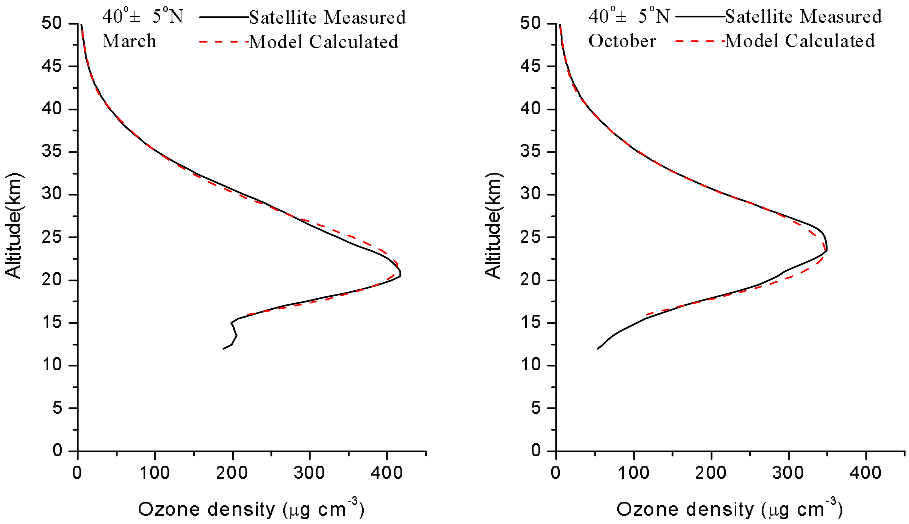

Fig. 2. Same as Fig. 1, but for the latitude band of $40° \pm 5°$N.

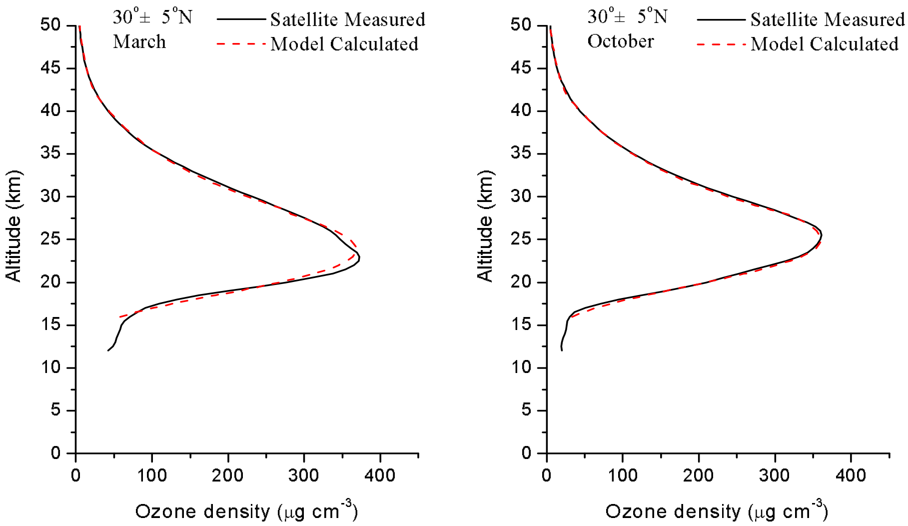

Fig. 3. Same as Fig. 1, but for the latitude band of $30° \pm 5°$N.

In the upper stratosphere between 43 km and 50 km, the vertical distribution of ozone is of the form:

$$\rho_{O_3} = 26.0 \exp[-(Z - 42.0)/4.8] . \tag{4}$$

The empirical coefficients in each month for the four latitude bands are listed in Tables 1–4 respectively. In practical use, the vertical distribution of stratospheric ozone can be calculated according to latitude, month and total ozone by employing these empirical equations.

4. Comparisons and analyses

In order to evaluate the model's accuracy, we first compare the model calculated ozone values and the monthly mean SAGEII/HALOE observed ozone profiles for different latitude bands. In the comparison, the modeled profiles are derived according to the latitude, month and total ozone coincident to the SAGEII/HALOE observations. Generally, the agreement between the observed and modeled ozone is very good. The differences [Differences (%)=(Model Calculated−Satellite Measured)/ Satellite Measured×100%] of the model calculated ozone concentrations relative to the SAGEII/HALOE satellite measurements are generally less than 15% between 16 km and 18 km; less than 5% between 19 km and 40 km; and less than 10% between 41 km and 50 km.

We used March and October cases as examples of comparison results. Shown in Figs. 1–4 are comparisons between the model calculated and the SAGEII/HALOE satellite observed vertical distributions of

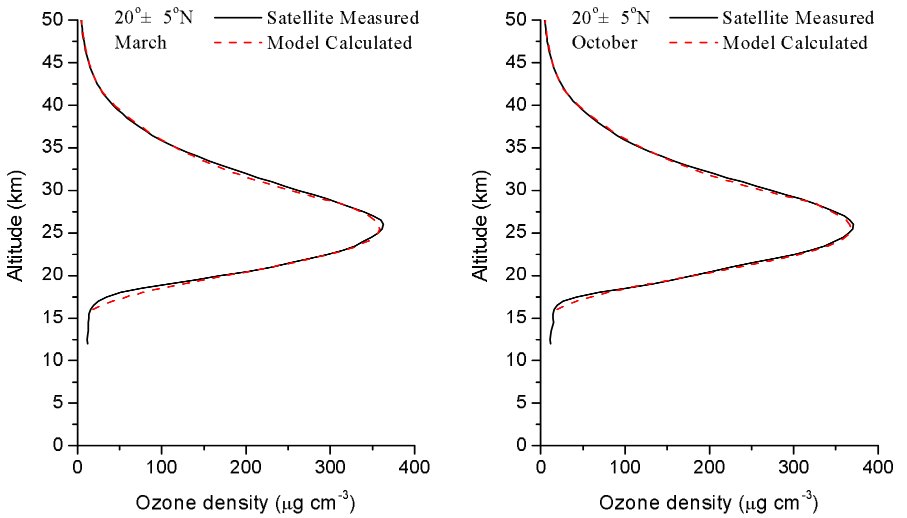

Fig. 4. Same as Fig. 1, but for the latitude band of 20° ±5°N.

ozone for March and October in the latitude bands 50°±5°N, 40°±5°N, 30°±5°N, and 20°±5°N respectively. We can see from Figs. 1–4 that the smooth curves (dashed lines) derived from the empirical model can well simulate the actual monthly mean ozone profiles (solid lines), with small biases throughout most of the stratosphere (16–50 km). This provides some justification that the empirical model is appropriate.

To further demonstrate the model's accuracy, we used balloon-borne ozonesonde measurements in Beijing (39.48°N, 116.28°E) for comparison. The ozonesonde data sets are measured by the GPSO3 ozonesonde system developed in China (Wang et al., 2003, 2004), which uses an electrochemical concentration cell (ECC) instrument and measures ozone from the ground to about 30 km. The ozone soundings were preformed from about 1350 to 1500 LST. The GPSO3 ozonesonde system was calibrated and checked each time before operation (Wang et al., 2003, 2004). The measurements made using this system were compared in the field with those of the Vaisala ozonesonde system from Finland (Wang et al., 2004; Xuan et al., 2004). The comparison results show that the ozone profiles measured by the two sonde systems agreed within 10% or less between 12 km and 27 km (Wang et al., 2004). This demonstrates that the GPSO3 ozonesonde measurements are reliable for testing our model's accuracy.

Figures 5–6 give the comparisons of the monthly mean ozonesonde and the model calculated ozone profiles for March and December 2004. The monthly mean ozonesonde profile of March 2004 is computed by averaging the 10 profiles performed on 9, 16, 23, 24, 25, 26, 27, 29, 30, and 31 March; and the ozonesonde profile for December 2004 is computed by averaging the 5 profiles performed on 1, 7, 14, 21, and 28 Decem-

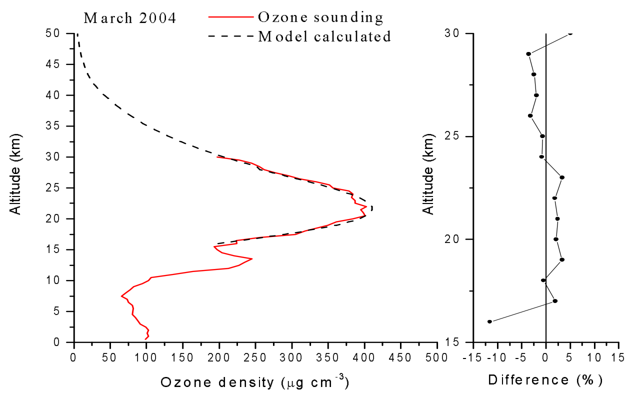

Fig. 5. Comparison of the model calculated ozone profile (dashed) and the 10-day average balloon-borne ozonesonde profile (solid) performed in Beijing for March 2004. Difference (%)=(Model Calculated−Ozonesonde)/Ozonesonde×100%.

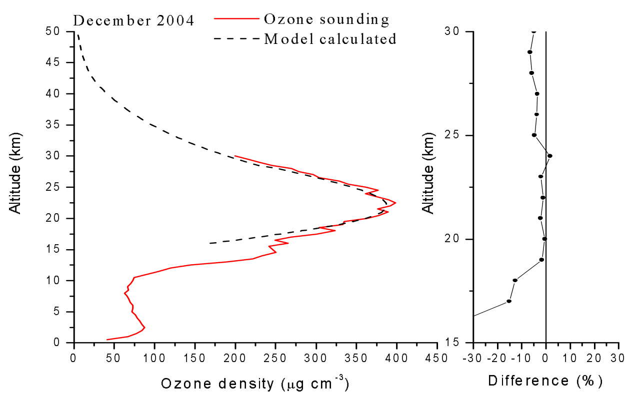

Fig. 6. Same as Fig. 5, but for the 5-day average from December 2004.

ber. The corresponding modeled profiles are derived according to the latitude (40°N), month (March or December), and the correlative total ozone measured by the ground-based Dobson instrument.

Figure 5 shows that the model calculated ozone profile is in good agreement with the ozonesonde profile over the altitude range of 17–30 km, with the differences generally less than 5%. In addition it can also be seen from Fig. 5 that the ozone sounding profile has a secondary peak between 10 km and 15 km, showing the complex variation of ozone distribution in the lowermost stratosphere.

Figure 6 shows that the model calculated ozone profile also agrees well with the ozonesonde profile from 19 km to 30 km, with the differences generally less than 5%. Below the 19 km level, the large differences around 16–18 km can be seen from Fig. 6, which is due to the variability of the ozone layer.

Overall there is reasonable agreement between the modeled and the sounding profiles between 19 km and 30 km, demonstrating that this model provides good simulations of the average features of stratospheric ozone distributions.

5. Summary and conclusions

We have developed an empirical model for estimating the vertical distribution of stratospheric ozone over China, based on SAGEII/HALOE and TOMS satellite ozone data sets. Employing this model, the vertical distribution of stratospheric (16–50 km) ozone can be calculated conveniently according to latitude, month and the total ozone. Comparisons of this model with the SAGEII/HALOE observations and with ozonesonde measurements have shown that the model calculated ozone profiles conform well to the monthly mean SAGEII/HALOE ozone profiles and balloon-borne ozonesonde profiles measured in Beijing. Results indicate that this empirical model provides a good simulation of the average pattern of the vertical distribution of stratospheric ozone over China.

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Erratum

Intercomparison of the Summertime Subtropical High from the ERA-40 and over East Eurasia and the western North Pacific

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On Page 119 of the printed edition (Issue 1, Vol. 26), the paper title should be "Intercomparison of the Summertime Subtropical High from the ERA-40 and NCEP/NCAR Reanalysis over East Eurasia and the Western North Pacific". The editorial office and the authors are sincerely sorry for any inconvenience this may have caused.