The Winter Ozone Minimum over the Subtropical Northwestern Pacific

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1. Vertical profile of ozone over the subtropical northwestern Pacific

Over the subtropical northwestern Pacific, a prominent ozone minimum of less than 235 Dobson Units (DU) is observed in winter (fig. 1).

In order to clarify the stratospheric and tropospheric contributions to the ozone minimum, the stratospheric ozone (above 100 hPa) was analyzed by vertically integrating Halogen Occultation Experiment (HALOE) ozone data, and the tropospheric ozone (below 100 hPa) was analyzed by subtracting the stratospheric ozone from the Total Ozone Mapping Spectrometer (TOMS) total ozone for the December, January and February (DJF) mean (Fig. 2). This technique is the same as that employed by Fishman et al. (1990), and Fig. 2 of the present study is similar to Figs. 7a, 8a, and 9a of their study, though they did not discuss the subtropical ozone minimum. The tropospheric ozone is low over the tropical Pacific, but the ozone minimum over the northwestern Pacific is not seen. On the other hand, the stratospheric ozone exhibits a clear minimum over the subtropical northwestern Pacific. At 20°N, 144°E, the total ozone in DJF is 13.6 DU less than the zonal mean. The tropospheric ozone contributes 2.7 DU (20%), and the stratospheric ozone contributes 10.9 DU (80%) to this reduction. Thus, the depletion occurs mainly in the stratospheric ozone.

The vertical profile based on HALOE climatology is examined to determine where the low-ozone layer is located in the stratosphere. Figure 3 shows the vertical profile of deviation from zonal mean ozone at 20°N, 144°E, where the ozone minimum occurs. It is clear that two distinct ozone minima exist, one at 10–15 hPa, and the other at 40–60 hPa. These two vertical ranges are responsible for the depletion leading to the northwestern subtropical ozone minimum. Although the middle stratospheric minimum (10–15 hPa) is stronger than the lower stratospheric minimum (40–60 hPa) in terms of mixing ratio, the lower stratospheric layer contributes more to the depletion of total ozone because of a density effect. As mentioned before, the stratospheric ozone at 20°N, 144°E, in DJF is 10.9 DU less than the zonal mean. The middle stratospheric ozone (5-25 hPa) contributes 3.6 DU (26% of the total ozone and 33% of the stratospheric ozone), and the lower stratospheric ozone (25-100 hPa) contributes 7.4 DU (54% of the total ozone and 68% of the stratospheric ozone) to this reduction. Above 5 hPa, the ozone contributes 0.1 DU (1% of the stratospheric ozone) increase to the total ozone.

The minimum in the lower stratosphere is probably caused by northward advection of ozone-poor air from the equatorial region, which is brought in from the troposphere by strong upward motion over the maritime continent. The similar mechanism which explains low water vapor in the subtropical northwestern Pacific has been discussed (Randel et al. 2001; Hatsushika and Yamazaki 2003). In the lower stratosphere, the ozone mixing ratio increases with latitude. Thus, northward advection from the equator toward the subtropics reduces the ozone in the subtropics. In the middle stratosphere, on the other hand, the ozone maximum is located at about 10°S, and the ozone density decreases toward northern high-latitudes. The northern subtropical Pacific is located to the south of the Aleutian High, and it is a reasonable hypothesis that this anticyclonic circulation brings ozone-poor air in the high latitude to the subtropical Pacific.

2. A simple chemical transport model

In order to confirm the above hypothesis regarding the middle stratospheric ozone minimum, a simple chemical transport model for ozone is constructed. As the ozone density peaks at 10 hPa in the vertical profile, the effect of vertical advection is considered to be small. Thus, the ozone mixing ratio χ is assumed to be transported by a two-dimensional horizontal wind field. The photo-chemical term is expressed by a Newtonian form so as to force the value to the photo-chemical equilibrium value χ^* with a time constant τ. The equation for the ozone mixing ratio is given as follows.

$$\frac{\partial \chi}{\partial t} = -\mathbf{V} \cdot \nabla \chi + k \nabla^2 \chi - \left(\chi - \chi^* \right) / \tau \qquad (1)$$

where **v** is the horizontal wind vector, and *k* is a diffusion coefficient. The model domain is set from the 10°S to 75°N, and ozone values at the boundaries are specified as climatological values. The wind is given by the European Centre for Medium Range Weather Forecasts (ECMWF) daily data, and an upwind scheme is used for advection. Starting from a zonally uniform initial condition, the model was integrated from October to March every year to match the period of HALOE data. The time constant τ was varied from 10 to 17 days from south to north (Dessler 2000), and *k* was set at 1.8×10^5 m^2s^{-1}, corresponding to the diffusion time-scale of 5 days. The values of χ^* were given based on the zonal-mean, 10-year mean HALOE data from 10°S to 40°N, and based on Keating and Young (1985) and Dutsch (1979) from 42.5°N to 75°N.

3. Results of the model simulation

Figure 4 shows the observed eddy ozone field (deviation from the zonal mean) from HALOE data, and Figure 5 shows the corresponding simulated field. Observed spatial patterns such as low ozone over the subtropical Pacific and high ozone from the subtropical Atlantic to Central America are captured well by this simple model. The simulated eddy ozone over the subtropical northwestern Pacific exhibits a peak in the ozone minimum in December, which accords with the observation. This December peak is attributed to seasonal variations in the meridional gradient of ozone and the strength of Aleutian High. In December the zonal mean ozone mixing ratio of middle latitudes (from 40°N to 70°N) is the lowest and thus the meridional gradient of ozone is the largest in midlatitudes. In addition, the northerly wind south of Aleutian High is the strongest in December than other months. These two factors contribute to bring high-latitude ozone-poor air into the subtropical north Pacific. Although the model is simple, the essential features of the observed eddy ozone fields are simulated very well, confirming that the middle stratosphere ozone minimum over the subtropical Pacific is attributable to southward transport of ozone-poor air associated with the Aleutian High.

Sensitivity tests were also conducted for the model parameters τ and *k*. Increasing τ to 30 days or decreasing *k* to 3.0×10^4 m^2s^{-1} (diffusion time-scale of 30 days) resulted in an increase in the magnitude of the ozone minima over the subtropical northwestern Pacific, as expected, but the differences were quite small. Thus, it was confirmed that the results are insensitive to the choice of parameters.

4. Summary and discussion

The causes of the prominent ozone minimum observed in winter over the subtropical northwestern Pacific were investigated using TOMS and HALOE data by constructing the vertical structure. The stratospheric ozone was found to be the main contributor to the depletion leading to the ozone minimum. Two distinct low-ozone layers were identified in the stratosphere, a middle stratosphere layer (10–15 hPa) and a lower stratosphere layer (40–60 hPa). The contributing percentages of winter ozone deviation from the zonal mean at 20°N are 54% from the lower stratosphere, 26% from the middle stratosphere and residual 20% from the troposphere. The cause of the mid-stratospheric low-ozone layer was attributed to southward transport of high-latitude ozone-poor air by atmospheric circulation associated with Aleutian High, as confirmed by a simple chemical transport model for the ozone minima at 10 hPa.

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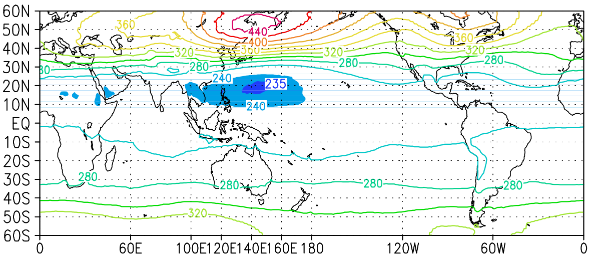

Fig. 1. January (1979–2002) total ozone climatology from TOMS data (DU) (values less than 240 DU are shaded)

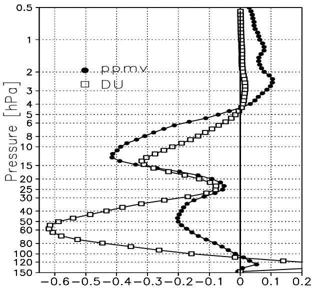

Fig. 3. Vertical profile of deviation from zonal mean ozone at 20ºN, 144ºE in winter (DJF) based on HALOE data (vertical axis: hPa, horizontal axis: ppmv and DU)

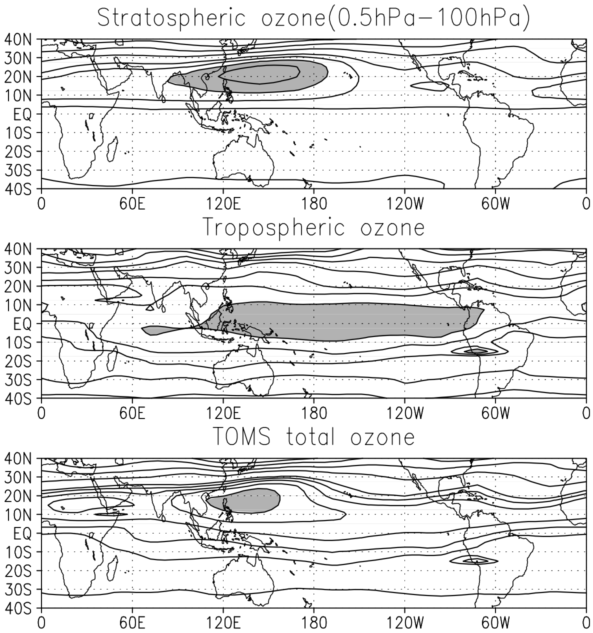

Fig. 2. Stratospheric ozone (top), tropospheric ozone (middle) and total ozone (bottom) in winter (DJF) (contours: DU)

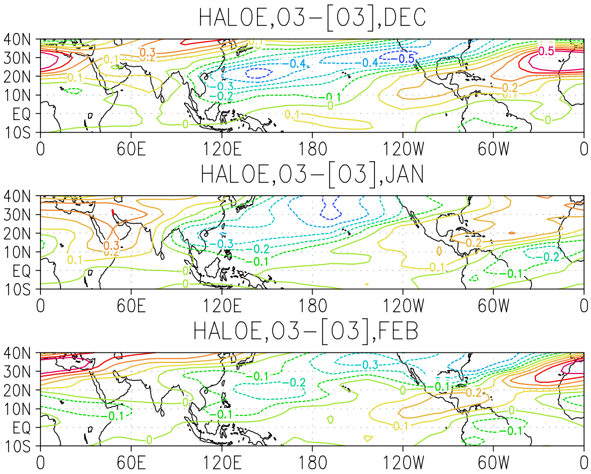

Fig. 4. Observed deviation from zonal mean ozone at 10 hPa from HALOE data for December (top), January (middle) and February (bottom) (contour interval: 0.1 ppmv)

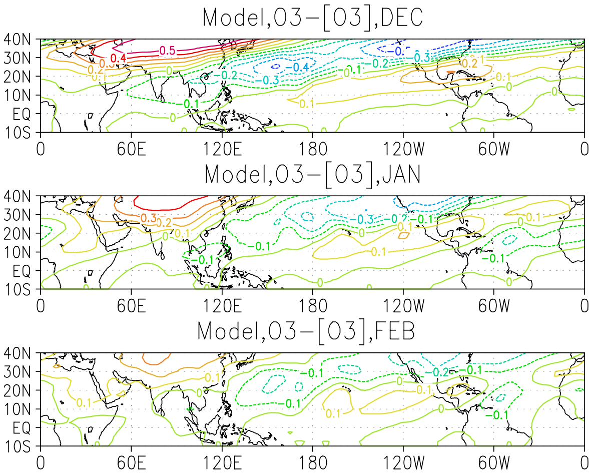

Fig. 5. Same as in Figure 8 except for simulated ozone.

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