Ozone vertical variations during a typhoon derived from the OMI observations and reanalysis data

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Typhoon is considered to play a key role in the dynamical exchange processes taking place between the troposphere and stratosphere. In this paper, the impact of typhoon on the ozone distribution in the upper troposphere and middle stratosphere is investigated using ozone profiles measured by Aura's Ozone Monitoring Instrument and meteorological fields from reanalysis data. During the passage of Typhoon Hai-Tang in 2005 over the western North Pacific, low values of ozone column above 200 hPa and ozone mixing ratio between the upper troposphere and the middle stratosphere (from 200 to 50 hPa) are observed right above the typhoon's track, a result due to the strong upward propagation of air associated with overshooting convection in typhoon. A comparative analysis of different stages of Hai-Tang suggests that in the region where typhoon has higher intensity the troposphere-to-stratosphere transport is enhanced. These results indicated that the typhoon has a significant impact on the ozone variation in the upper troposphere and the middle stratosphere.

typhoon, overshooting convection, Ozone Monitoring Instrument, ozone vertical profiles, ozone distribution

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Deep convection in typhoons (or tropical cyclones) provides a preferred condition for stratosphere-troposphere exchange [1,2] that causes the variability of ozone in the upper troposphere and lower stratosphere. The injection of tropospheric ozone-poor air into the lower stratosphere near the typhoon's eye has been observed based on the aircraft measurements [3–7] and satellite data [8–11]. Moreover, stratospheric ozone-rich air intrusion into the troposphere due to the subsidence in the eye of typhoons has been reported [3,5,12,13]. These typhoon-related ozone episodes are generally believed to be the results of tropospheric air upwelled by deep convection and ozone-rich stratospheric air down-

welled by intrusion [6,8,10,13]. Although there are discrepancies between the total column ozone derived from satellites and aircraft observations in typhoons' eyes [7,12], the regions of high column ozone inside the eye regions are observed during intense stages of typhoons [6]. Additionally, typhoon not only influences the local ozone budget, but also has an impact on the ozone meridional transport [14]. Based on backward trajectory analysis, ozone transported between midlatitude and tropics was influenced by the large-scale circulation coupled with a typhoon [7,14,15].

However, the variability of ozone vertical structure during the typhoon processes has not been well investigated. Fortunately, the Ozone Monitoring Instrument (OMI) launched on the National Aeronautics and Space Administration

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(NASA) Aura platform in July 2004 [16] provides a unique opportunity to investigate ozone vertical distribution extending from troposphere to stratosphere. In this study, Typhoon Hai-Tang in July 2005 is captured by OMI over the western North Pacific. A comparative analysis of different stages of Hai-Tang, category 1 on 13 July and category 4 on 17 July, was conducted to examine the different contributions of weak and intense typhoons to the exchange between troposphere and stratosphere. Two square regions, S1 and S2, which are occupied by the centers of Hai-Tang at 0600 UTC on 13 July and at 0600 UTC on 17 July, are selected. Ozone statuses within the selected regions during the typhoon's passage (hereafter called TC), before the typhoon (hereafter called pre-TC) on 11 July, and after the typhoon (hereafter called post-TC) on 15 July for S1 and 17 July for S2 are calculated for comparison.

Two remote sensing data sets, i.e. the average rain rate between 2 and 4 km from the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) 2A25 data and ozone profiles from the version 3 OMO3PR products of

OMI are used in this work. The rain rate data with a horizontal resolution of 4.5 km is available at the Tropical Cyclone Database (<http://www.eorc.jaxa.jp/TRMM/typhoon>) maintained by the Japan Aerospace Exploration Agency (JAXA)/Earth Observation Research and application Center (EORC). The ozone profiles are provided by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (<http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI>). The ozone profiles are given in terms of the layer-columns of ozone in Dobson Unit (DU) for an 18-layer atmosphere, with the layers nominally bounding by the pressure levels (surface pressure, 700, 500, 300, 200, 150, 100, 70, 50, 30, 20, 10, 7, 5, 3, 2, 1, 0.5, 0.3 hPa). The data have a horizontal resolution of 65 km $\times$ 48 km. The comparison of ozone profiles from OMI and Microwave Limb Sounder (MLS) [17] shows that OMI ozone profiles in the northern sub-tropics (15°–30°N) show a bias of –15%–10% and the standard deviations of the differences are 2%–7% above 50 hPa and within 12% between 50–215 hPa. Moreover, ozone column above 200 hPa (OC200) was

Figure 1 (a) and (b) Rainfall rate (shaded: mm h⁻¹) and sea level pressure (contour: hPa), and (c) and (d) OC200 (shaded: DU) with sea level pressure (contour) at 0600 UTC 13 July and 0600 UTC 17 July, respectively. The southwest-northeast cross sections of ozone were shown by the black lines AB and CD; the eyes of typhoon were indicated by red crosses; the research areas for mean ozone profiles were shown by dotted squares S1 and S2. (e) and (f) OC200 (unit: DU) along lines AB and CD before (pre-TC), during (TC) and after (post-TC) Hai-Tang, respectively. The red dotted lines indicated the locations of typhoon eye.

employed. Liu et al. [18] in 2010 demonstrated that OMI retrieval errors in stratospheric ozone columns down to 215 hPa are 1.6–4 DU. Additionally, the effect of cloud in the troposphere can be neglected in this ozone column product.

In addition, the sea level pressure (SLP) and vertical velocities at 500 hPa (ω_{500}) on $1^\circ \times 1^\circ$ grid at every six hours (0000, 0600, 1200, and 1800 UTC) based on National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis data (<http://cfs.ncep.noaa.gov/cfsr/>) are used to quantify the typhoon's strength. The potential vorticity (PV) obtained from European Centre for Medium-Range Weather Forecasting (ECMWF) reanalysis project (ERA-Interim) was used as a dynamical tracer for the exchange process between troposphere and stratosphere. The PV data are available four times daily on a $0.75^\circ \times 0.75^\circ$ grid with 37 pressure levels from 1000 to 1 hPa.

Typhoon Hai-Tang formed on 11 July 2005 in the western subtropical Pacific. As it moved westward, it continued to gain strength and reached category 5 on 16 July. Hai-Tang landed on eastern coast of Taiwan as a category-3 typhoon on 18 July. OMI provides relatively complete measurements on 13 and 17 July, 2005, when Hai-Tang was located at 22.4°N , 148.3°E and at 22.1°N , 125.1°E reaching category 1 and 4, respectively. As depicted in Figure 1(a), asymmetric precipitation of Hai-Tang was evident on 13 July. Similar asymmetric typhoon rainfall with a larger rainfall area was observed on 17 July in Figure 1(b). Figure 1(c) displays that a relatively lower OC200 (250 DU) coincided with larger rain rates ($>5 \text{ mm h}^{-1}$) occurred in the southwest quadrant of Hai-Tang, while higher OC200 (>260 DU) was accompanied with lower rain rates ($<0.5 \text{ mm h}^{-1}$). OC200 decrease over a larger area was found in the southwest

Figure 2 (a) and (c) Mean ozone profiles in S1 and S2 before (Pre-TC), during (TC) and after (Post-TC) Hai-Tang, respectively. (b) and (d) Differences (solid) and difference changes (dashed) of ozone profiles between typhoon and pre-typhoon (Diff I, PCDiff I) and between typhoon and post-typhoon (Diff II, PCDiff II) for S1 and S2, respectively.

and southeast quadrants of Hai-Tang when the typhoon was stronger (Figure 1(d)). From the OC200 along line AB (Figure 1(e)), it is seen that higher ozone of 256–265 DU occurred in pre-TC in contrast to lower ozone of 255–260 DU dominated the typhoon region (20° – 22.7° N) in TC. The OC200 along line AB were 267–275 DU in post-TC. Along line CD (Figure 1(f)), OC200 prior to the arrival of typhoon was 256–261 DU. OC200 change attained to -5.5 DU. OC200 along line CD were 270–276 DU in post-TC. OC200 changes in the cyclone activity region (-4.3 DU on 13 July and -5.5 DU on 17 July) are larger than the OMI retrieval errors in stratospheric ozone columns down to 215 hPa (1.6–4 DU) [18]. The magnitude and extent of the decrease in OC200 induced by the typhoon with higher intensity are larger than those by the weak typhoon.

To elucidate the variability of ozone profile induced by Hai-Tang, mean ozone profiles of regions S1 and S2 (Figure 1(c) and (d)) in three periods (pre-TC, TC and post-TC) are analyzed. As depicted in Figure 2(a) and (c), ozone decreased in TC in both S1 and S2. Furthermore, difference and difference change of ozone profiles between TC and pre-TC (TC minus pre-TC, Diff I) and that between TC and post-TC (post-TC minus TC, Diff II) are shown in Figure 2(b) and (d). Ozone decreased between 200 and 50 hPa in Diff I in S1. The corresponding is about -12% – 2% change. During Diff II, ozone increase attained to 10% in the 50–200 hPa. As for S2 in Figure 2(d), ozone decreased in the 50–200 hPa during Diff I. The corresponding is about -22% – -3% change. During Diff II in S2, ozone increased between 50 and 200 hPa. The difference changes of ozone profiles in the cyclone activity region, -12.2% at 175 hPa on 13 July and -22.9% – -15.4% in 125–200 hPa on 17 July, are evi-

dent with the consideration of the uncertainties of 12% between 50–215 hPa in OMI ozone profiles over the northern sub-tropics (15° – 30° N) [17].

In order to depict the vertical structure of ozone in more detail, the anomalies in ozone mixing ratio between 50 and 200 hPa along line AB on 13 July and line CD on 17 July are shown in Figure 3. The ozone anomalies are obtained from the mean ozone transection averaged from pre-TC to post-TC according to their own time series. Figure 3(a) illustrates that Hai-Tang caused a decrease in ozone mixing ratio from 200 to 50 hPa. In comparison with the category 1 typhoon on 13 July, the strong updraft ($\omega_{500} < -1 \text{ Pa s}^{-1}$) in the category 4 typhoon caused ozone being diluted from 200 to 50 hPa with a larger magnitude on 17 July along CD. In addition, around the eyewall low PV values extend upward from the upper troposphere to the lower stratosphere on 17 July, suggesting the penetration of deep convection around the eyewall into the stratosphere.

In conclusion, based on the state-of-the-art OMI ozone profile, the impact of Typhoon Hai-Tang (2005) on stratospheric ozone was investigated in this study. The updraft extended vertically upward from upper troposphere indicates the presence of overshooting with ozone poor air that has penetrated into the stratosphere during the typhoon. A comparative analysis for different stages of Hai-Tang showed that the exchange process between troposphere and stratosphere is enhanced in the region where typhoon has a higher intensity. Further work based on higher resolution measurements and cloud-resolving model simulations are required to better understand the dynamical processes by which a typhoon contributes to the upper troposphere and lower stratosphere.

Figure 3 Ozone anomalies and potential vorticity (contours: $10^6 \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$) distribution between 200 and 50 hPa, and ω_{500} (line plots: Pa s^{-1}) along lines (a) AB and (b) CD on 13 and 17 July, respectively.

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