AGU ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2020EF001635

Key Points:

- Western Pacific typhoons impact 46.3% (44.9%) of ozone profiles in Hong Kong (Naha) from July to October of 2000–2017
- Ozone values below 60 ppbv near the tropopause in Hong Kong and Naha are caused by vertical transport of ozone-poor air by typhoon convection
- Typhoons reduce ozone by 20–60 ppbv compared to 18 years mean ozone profile in the upper troposphere and lower stratosphere

Supporting Information:

- Table S1

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Citation:
Li, D., Vogel, B., Müller, R., Bian, J., Günther, G., & Riese, M. (2021). Tropical cyclones reduce ozone in the tropopause region over the western Pacific: An analysis of 18 years ozonesonde profiles. *Earth's Future*, *9*, e2020EF001635. https://doi.org/10.1029/2020EF001635

Received 12 JUN 2020
Accepted 25 JAN 2021

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Tropical Cyclones Reduce Ozone in the Tropopause Region Over the Western Pacific: An Analysis of 18 Years Ozonesonde Profiles

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Abstract Typhoons play a key role in causing low ozone concentrations in the upper troposphere and lower stratosphere (UTLS) over the western Pacific. In this study, 18 years records (2000–2017) of balloon-borne ozone measurements in Hong Kong (22.3°N, 114.2°E) and Naha (26.2°N, 127.7°E) are combined with trajectory calculations to quantitatively assess the impact of western Pacific typhoons on ozone in the UTLS. The results show that 46.3% (44.9%) of the ozone profiles in Hong Kong (Naha) are impacted by western Pacific typhoons from July to October, with negative ozone anomalies exceeding −20%. Vertical transport by intense typhoons affects 16.8% (18.8%) of the ozone profiles in Hong Kong (Naha) with even larger negative anomalies (<−40%). Vertical transport of tropical cyclones reduces ozone by about 20–60 ppbv compared to the mean ozone profile near the tropopause. Ozone values below 60 ppbv in the upper troposphere in Hong Kong and Naha are mainly caused by the uplift in the western Pacific typhoons and by horizontal transport within the Asian summer monsoon (ASM) anticyclone. The horizontal transport in the ASM anticyclone has larger contributions to the low ozone values measured over Hong Kong than over Naha.

Plain Language Summary Ozone profiles from July to October during 2000–2017 in Hong Kong and Naha are used to analyze the impact of western Pacific cyclones on ozone in the upper troposphere and lower stratosphere. During the summer season, typhoons over the western Pacific influence 46.3% (44.9%) of the ozone profiles in Hong Kong (Naha) based on the trajectory calculations of air masses. We also find that in Hong Kong (Naha) intense typhoons contribute to large negative ozone anomalies (<−40%) for 16.8% (18.8%) of the profiles. Vertical transport associated with typhoons and the horizontal transport of the Asian summer monsoon anticyclone reduces ozone by about 20–60 ppbv near the tropopause in Hong Kong and Naha.

1. Introduction

Deep convection associated with tropical cyclones plays a major role in the exchange between the stratosphere and the troposphere (Baray et al., 1999; Venkat Ratnam et al., 2016); it may cause both upward and downward transport. Stratospheric ozone-rich air can be transported into the troposphere by stratospheric intrusions (Das, 2009; Li et al., 2018; Pan et al., 2014) and boundary layer air with low ozone can be uplifted into the upper troposphere and lower stratosphere (UTLS) region (Bian et al., 2020; Danielsen, 1993; Das et al., 2016; Pan et al., 2015; Randel & Park, 2006). In previous analyses of ozone sondes measurements from the Southern Hemisphere Additional Ozonesonde (SHADOZ) network over the tropics, convective and wave signatures were found in ozone vertical profiles (Thompson et al., 2010, 2011). The airborne campaign, Convective Transport of Active Species in the Tropics (CONTRAST), conducted over Guam (13.5°N, 144.8°E), revealed that the tropospheric ozone minimum of ~20 ppbv at ~12–14 km was controlled by convective outflow (Pan et al., 2015).

The western Pacific typhoon season peaks from July to October in the Northern Hemisphere (Matsuura et al., 2003). Several observations have shown that typhoon convection can lift ozone-poor air from the marine boundary layer into the tropopause region over the Pacific region (Li et al., 2017, 2020; Minschwaner et al., 2015; Newton et al., 2018; Vogel et al., 2014). As a result, low-ozone values are measured in the upper troposphere within typhoons or hurricanes (Cairo et al., 2008; Fu et al., 2013). Li et al. (2017,2020) show that tropical cyclones over the western Pacific decrease upper tropospheric ozone over the Tibetan Plateau via uplifting of marine ozone-poor air masses to the upper troposphere and subsequent long-range transport by the Asian summer monsoon (ASM) anticyclone. Coupling between the Asian summer monsoon circulation and typhoon convection will impact the ozone concentration in the UTLS over the western Pacific and the ASM region. The UTLS ozone variation can cause a change in the regional radiative budget of the atmosphere. Therefore, quantifying the ozone variation in the UTLS is important for surface climate, because even small changes of ozone in the UTLS have an impact on surface temperatures (Riese et al., 2012). However, previous studies were usually based on individual cases over a short time period (single to several days) without giving a climatological effect. Here, we derive a quantitative estimate of the impact of western Pacific typhoons on ozone in the UTLS based on measurements in Hong Kong and Naha for an 18-year period between 2000 and 2017.

Hong Kong (22.31°N, 114.17°E) and Naha, Japan (26.21°N, 127.69°E), are both sites of the World Meteorological Organization (WMO) Ozone and Ultraviolet Data Center (WOUDC), and have both long-term observations of ozone profiles over the western Pacific region since 2000. These high-quality and high-resolution balloon-borne measurements allow us to deduce a quantitative estimate of the frequency and intensities of western Pacific typhoons on ozone variability in the UTLS. Using 18 years (2000–2017) measurements at Hong Kong and Naha, we find that about 46% of the measured ozone profiles are impacted by western Pacific typhoons from July to October and that large negative ozone anomalies (exceeding 40%) are caused by intense typhoons affecting 17%–19% of the profiles.

2. Data and Method

Tracks and intensity of tropical cyclones are obtained from the Tokyo-Typhoon Center for the period 2000–2017. The tracks are recorded every 6 h with the lowest pressure, center latitude, and longitude of tropical cyclones. Tropical cyclones are used with grades for class 3 (Tropical Storm), 4 (Severe Tropical Storm), and 5 (Typhoon) with maximum wind speed great than 63, 88.9, and 118.5 km h^{-1}, respectively (Figure 1).

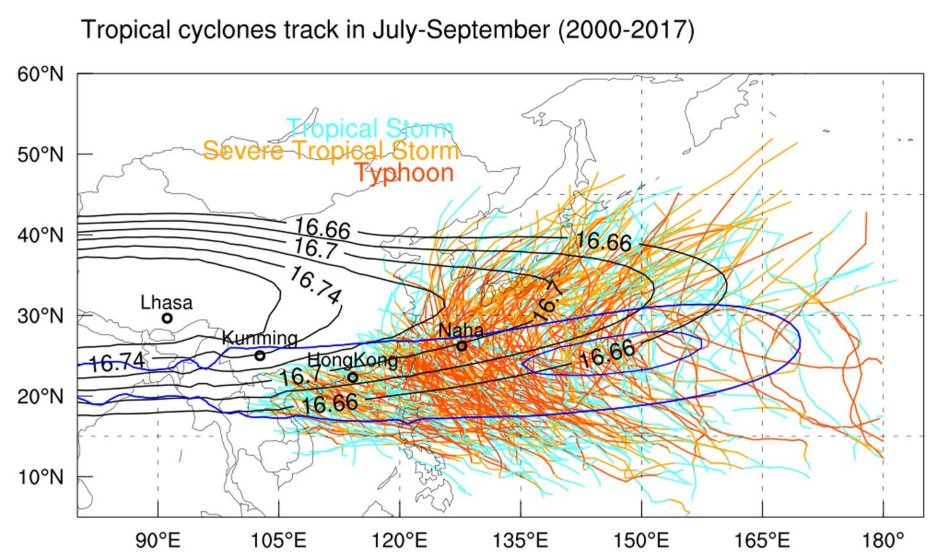

Figure 1. The tracks of tropical cyclones over the western Pacific from July to October during 2000–2017 (The color indicate the category of the tropical cyclone). The mean geopotential height at 100 hPa (>16.66×10^3 gpm) for July-September (black line) and for October (blue line). Because of the decay of the ASM anticyclone in October the mean geopotential height is indicated separately. The circles mark the location of Lhasa, Kunming, Hong Kong, and Naha. ASM, Asian summer monsoon.

Around 326 cyclones formed over the western Pacific during 2000–2017, with the typhoon season peaking from July to October.

Ozone profiles for Hong Kong and Naha between July and October (2000–2017) are obtained from the WOUDC. For Naha, the Japanese ozonesonde (KC type, Kobayashi & Toyama, 1966) is used before November 13, 2008, after that day the electrochemical concentration cell (ECC) ozonesonde is used until February 2018. Detailed information about KC type and ECC ozonesonde are given by Kobayashi and Toyama (1966) and Komhyr et al. (1995). Ozone concentrations are always measured by ECC ozonesondes in Hong Kong since 2000. Profiles are recorded at 1 s frequency by radiosondes with the ozonesondes. From July to October during the period of 2000–2017, there are 249 (265) ozone soundings for Hong Kong (Naha). More than 80% of balloons were routinely launched every Wednesday at 05:00 UTC at both stations to measure the vertical ozone profile from the surface to approximately 30–35 km altitude. When the balloon burst altitude is lower than the tropopause, the tropopause height cannot be calculated, therefore four profiles in Hong Kong will not be used in this study.

The FengYun-2G (Feng and Yun mean "winds and clouds" in Chinese), or FY-2G in acronym are the geostationary meteorological satellite series of China, organized and operated by the National Satellite Meteorological Center of China Meteorological Administration. FY-2 G was launched on December 31, 2014 with a five-channel Stretched Visible and Infrared Spin Scan Radiometer (S-VISSR) as part of the payload to track cloud motion. Here, we use cloud top temperature (CTT) to determine the position and the altitude range of tropical cyclones.

The Chemical Lagrangian Model of the Stratosphere (CLaMS) trajectory module (Konopka et al., 2012; Pommrich et al., 2014) was used to calculate 40 days diabatic backward trajectories for ozone profiles in Hong Kong and Naha. These diabatic trajectory calculations employ a hybrid σ-potential temperature coordinate, but above about 300 hPa, that is, in the stratosphere and upper troposphere, the vertical coordinate is exactly the potential temperature and the vertical velocity is determined solely by the total heating rate (Pommrich et al., 2014). Total diabatic heating rates include clear-sky radiative heating, cloud radiation, latent heat release, as well as turbulent and diffusive heat transport (Fueglistaler et al., 2009) for the upper troposphere and stratosphere (Ploeger et al., 2010; 2011; Schoeberl & Dessler, 2011; Schoeberl et al., 2003). The European Center for Medium-range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) (Dee et al., 2011) is used to drive the CLaMS trajectories. ERA-Interim input wind field is recorded on a $1 \times 1°$ grid every 6 h. Similar trajectory calculations were used to investigate the ozone distribution in the UTLS over the Tibetan Plateau by Li et al. (2017, 2018, 2020).

Ozone mixing ratios at UTLS altitudes over the western Pacific and associated coastal regions (e.g., Hong Kong and Naha) are influenced by different processes: regional convection, tropical cyclones, stratospheric intrusions, air in the ASM anticyclone, and advection from eastern China and the tropical region. Processes that enhance ozone mixing ratios in the UTLS over the western Pacific are stratospheric intrusions exporting ozone-rich air from the extratropical lower stratosphere (Li et al., 2018) and the advective transport from ozone-rich surface air from eastern China. During the monsoon season, vertical transport associated with regional convection significantly decreases ozone concentrations around 7–13 km (Randel & Park, 2006). Tropical cyclones consist of bands of cumulus convection clouds, which extend up to the tropopause region and have the potential to uplift ozone-poor marine air into the UTLS (Emanuel, 2003; Li et al., 2017, 2020). In order to investigate the origin of low ozone mixing ratios in the UTLS caused by tropical cyclones, our analysis focuses on the altitude range between 12.5 km and the tropopause. CLaMS 40 days backward trajectories are calculated (started every second) for air parcels between 12.5 km and the tropopause for July to October of 2000–2017. The trajectories for air parcels with negative ozone anomalies lower than −20% (−40%) with the thickness great than 1(3) km compared to the averaged ozone profile are selected and further analyzed for Hong Kong and Naha within this study.

In a previous case study, Li et al. (2017) show that low ozone mixing ratios in the ASM anticyclone can be caused by the strong vertical transport of tropical cyclones and subsequent horizontal transport by the flow of the ASM anticyclone. The ascent rate is defined as the change in the potential temperature (θ) per day $(\theta_{t+\delta t} - \theta_t)/\delta t$ for air parcels along each CLaMS back-trajectory. When the ascent rate is greater than 9 K day^{-1} (in a 24-h period), a strong uplift process of the air parcel along the trajectory will be detected

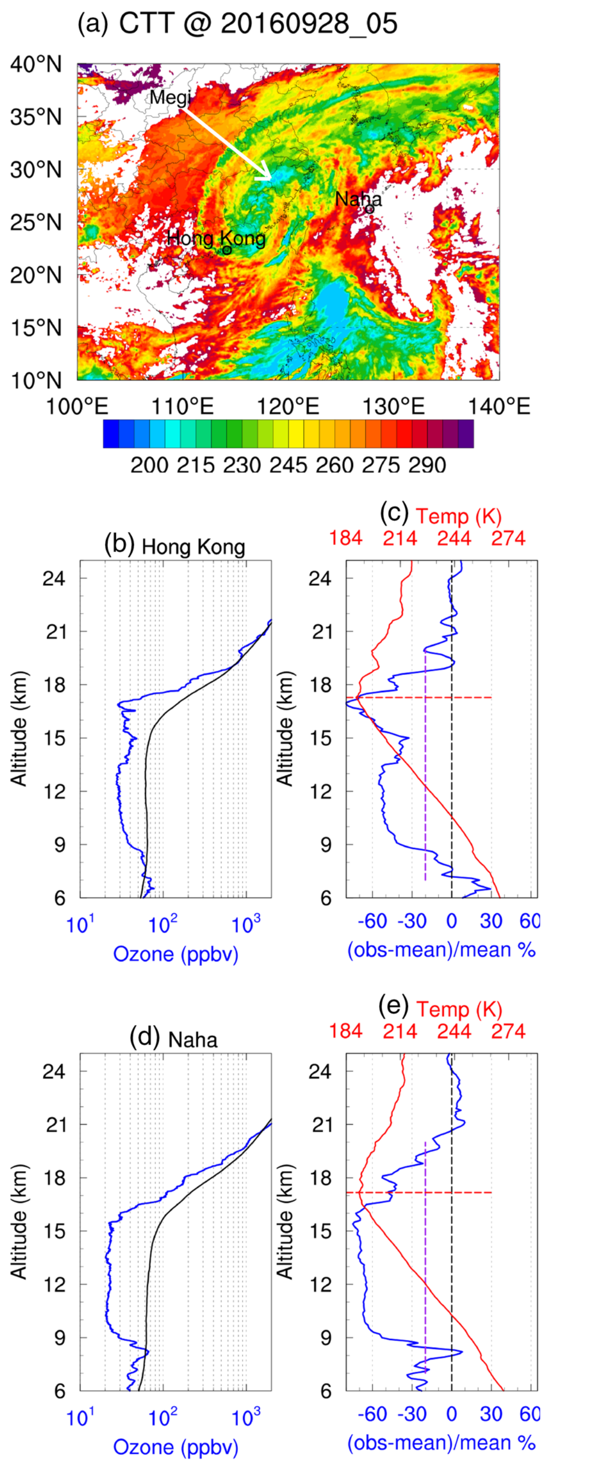

Figure 2. The cloud top temperature of typhoon Megi (marked by the arrow) on September 28, 2016 (a). Vertical profile of ozone (blue) on September 28, 2016 and mean ozone over the period July-October for the years 2000–2017 (black) for Hong Kong (b) and Naha (d). Relative ozone anomaly ([sonde-mean]/mean, blue) and vertical profile of temperature (red) for Hong Kong (c) and Naha (e). The dashed horizontal red lines show the thermal lapse rate tropopause. Dashed vertical lines denote the zero and −20% ozone anomaly.

(Li et al., 2018). Furthermore, the geographical locations for strong uplift (>9 K day^{-1}) of air parcels, fall within the range 10° around the center of tropical cyclone, which is used to identify the cases impacted by western Pacific typhoons in Hong Kong and Naha. The names of cyclones and the horizontal transport time for the air parcels from the top of tropical cyclones to the sites in Hong Kong and Naha are given in Table S1.

Our findings show that up to 32% of all ozone profiles measured over Hong Kong and Naha within 1 week are impacted by tropical cyclones (see Table S1). About 4% of the ozone profiles are impacted by tropical cyclones from the Indian Ocean and regional deep convection.

3. Results

Figure 1 shows the tracks of 326 tropical cyclones from the Tokyo-Typhoon Center and the mean geopotential height at 100 hPa for July-September and for October during the period of 2000–2017 using the ERA-Interim reanalysis data. Typhoons are marked with grades 3–5, from tropical storms to severe tropical storms to typhoons. Naha is located in the region where most cyclones change their direction of movement from north-western to northeastern tracks and is therefore impacted by 52 tropical cyclones near Naha within a radius of 200 km (Figure 1). Hong Kong is only impacted when tropical cyclones move westwards and is influenced by 34 tropical cyclones within 200 km from Hong Kong. Naha is more frequently influenced by tropical cyclones than Hong Kong according to the cyclone tracks distribution, and possibly is impacted from the northerly wind flow on the eastern edge of the ASM anticyclone. Hong Kong appears to be under the influence of northeasterly flow on the southeastern edge of the ASM anticyclone. Previous studies show that ozone-poor air masses were even observed in the UTLS over the Tibetan Plateau by balloon-borne measurements from Lhasa and from Kunming in East China (their locations are indicated in Figure 1), which were caused by tropical cyclones over the western Pacific (Li et al., 2017, 2020).

To better explain the method used in this work, we present a case study of typhoon Megi which occurred in September 2016. The same method is used to infer the climatological results from 2000 to 2017. The cloud top temperature (K), which is indicating convection, is shown in Figure 2a. The blue color is used to mark low temperatures, which means deep convection with a high cloud top. Hong Kong and Naha are located at the edge of landfalling typhoon Megi on September 28, 2016, the day that the balloon was launched in Hong Kong and Naha. As the tropical cyclone moves toward northwest, Hong Kong and Naha are located slightly away from the center of the cyclone. Ozone profiles for Hong Kong (Naha) on September 28, 2016 show a low ozone structure between 9 and 19 km with values ~30 ppbv (~20 ppbv) (Figures 2b and 2d). Ozone values at 9–19 km on September 28 in Hong Kong and Naha are significantly lower than the climatological mean ozone, which is calculated from July to October of 2000–2017. Ozone profiles are normalized to the climatological mean profile to show the relative ozone anomalies (Figures 2c and 2e). In Hong Kong, the tropospheric ozone anomaly is less than −50%, with the largest negative anomalies of about −80% occurring at 17 km around the tropopause. In Naha, the negative ozone anomalies are lower than −70%

Table 1
Numbers of Ozone Profiles Impacted by Upward Transport of Tropical Cyclones From the Western Pacific, and by Transport Caused by Other Processes Such as Stratospheric Intrusions (Ozone-Rich Air), Air in the ASM Anticyclone (Ozone-Poor Air), and Transport From Eastern China (Ozone-Rich Surface Air) and the Tropical Region for July-October From 2000 to 2017 in Hong Kong (Naha)

Year	Tropical cyclones	Others	Total
2000	5 (5)	12 (7)	17 (12)
2001	0 (9)	0 (6)	0 (15)
2002	1 (9)	3 (7)	4 (16)
2003	7 (5)	11 (9)	18 (14)
2004	8 (8)	8 (5)	16 (13)
2005	10 (9)	7 (7)	17 (16)
2006	5 (8)	8 (7)	13 (15)
2007	8 (3)	8 (8)	16 (11)
2008	7 (6)	8 (8)	15 (14)
2009	9 (6)	8 (8)	17 (14)
2010	5 (1)	10 (10)	15 (11)
2011	6 (3)	9 (13)	15 (16)
2012	6 (7)	10 (9)	16 (16)
2013	5 (7)	8 (10)	13 (17)
2014	8 (7)	9 (8)	17 (15)
2015	9 (9)	4 (8)	13 (17)
2016	11 (11)	2 (5)	13 (16)
2017	3 (6)	6 (11)	9 (17)
Total	113 (119)	131 (146)	244 (265)
Percent	46.3% (44.9%)	53.7% (55.1%)	100% (100%)

in the middle and upper troposphere. In addition, the negative ozone anomalies reach clearly above the temperature lapse rate tropopause at 17.3 km in Hong Kong and at 17.2 km in Naha. These observations indicate that low ozone values in the UTLS occur in the outflow of deep convection associated with typhoons. The relative ozone anomaly of −20% is marked as a vertical dashed line in Figures 2c and 2e. The back-trajectories for air parcels with ozone anomaly less than −20% are used to calculate the contributions of tropical cyclones and in particular of typhoons to low ozone values found in the UTLS in Naha and Hong Kong.

Table 1 shows the ozone profiles in the 18 years (2000–2017) data record of ozone measurements from July to October in Hong Kong (Naha). Ozone profiles are divided into two groups: (1) low ozone value (ozone anomalies less than −20%) impacted by tropical cyclones as Figure 2b shows, (2) other category such as stratospheric intrusions (ozone-rich air) (Li et al., 2018), air in the ASM anticyclone and advection transport from eastern China (ozone-rich surface air) and the tropical region. In total, 113 (119) profiles were influenced by tropical cyclones over the western Pacific compared to total ozone profiles 244 (265) in Hong Kong (Naha). Thus, tropical cyclones impact Hong Kong and Naha ozone profiles up to 46.3% and 44.9% between 2000 and 2017.

Mean ozone profiles with 1σ standard deviation impacted by intense (normal) typhoons and by other processes such as stratospheric intrusions, air in the ASM anticyclone and advection transport from eastern China and the tropical region are shown for the stations Hong Kong and Naha (Figures 3a, 3b, 3e, and 3f). According to the statistical results, typhoons mainly reduce ozone in the upper troposphere, and 2 km above the thermal lapse rate tropopause and increase ozone in the lower stratosphere. The mean tropopause height is about 16.78 km for all typhoon cases in Hong Kong and 16.52 km in Naha. Ozone is reduced by ~20–60 ppbv at 2–6 km above and below the tropopause under the influence of tropical cyclones relative to the climatological mean ozone profile. Similar vertical structures are also observed in Hanoi (21°N, 106°E), Vietnam (Thompson et al., 2012, their Figure 5a) in the tropics.

Differences between typhoon-influenced and mean ozone profiles are shown relative to the tropopause both for intense typhoons (solid red line), normal typhoons (solid blue line), and others (solid green line; Figures 3c and 3g) and, similarly, for temperature (Figures 3d and 3h). Ozone values around the tropopause are most strongly influenced by typhoons. Thus, the outflow of typhoon convection cools the region 2 km above and below the tropopause in Hong Kong and Naha by 1–3 K (Figures 3d and 3h). A decrease in the tropopause altitude was observed within 500 km of the center of tropical cyclones over the north Indian Ocean (Venkat Ratnam et al., 2016).

Figures 4a and 4c show the relative frequency distribution of ozone (12.5–17 km) impacted by typhoons and by other processes in Hong Kong and Naha. The relative frequency is calculated as the number of ozone values (every 10 ppbv) between 12.5 and 17 km divided by the total number of ozone profiles impacted by tropical cyclones. The relative frequency of ozone peaks at 0.11 with ozone values between 20 and 60 ppbv under the influence of typhoons, and ozone values between 60 and 180 ppbv for other processes in Hong Kong (Figure 4a). The ozone relative frequency peaks at 0.07 in Naha (Figure 4b). Air parcels with low ozone anomalies (<−20%) in Hong Kong (12,814 counts in total) and Naha (5,960 counts) are mainly uplifted by tropical cyclones from the western Pacific region based on the CLaMS trajectories, a minor fraction of trajectories was uplifted from the continental region (Figures 4b and 4d).

Ozone-poor air from the western Pacific will be transported to Hong Kong and Naha via two different pathways; one is from the top of a typhoon to Hong Kong and Naha directly within 1 week (black lines in

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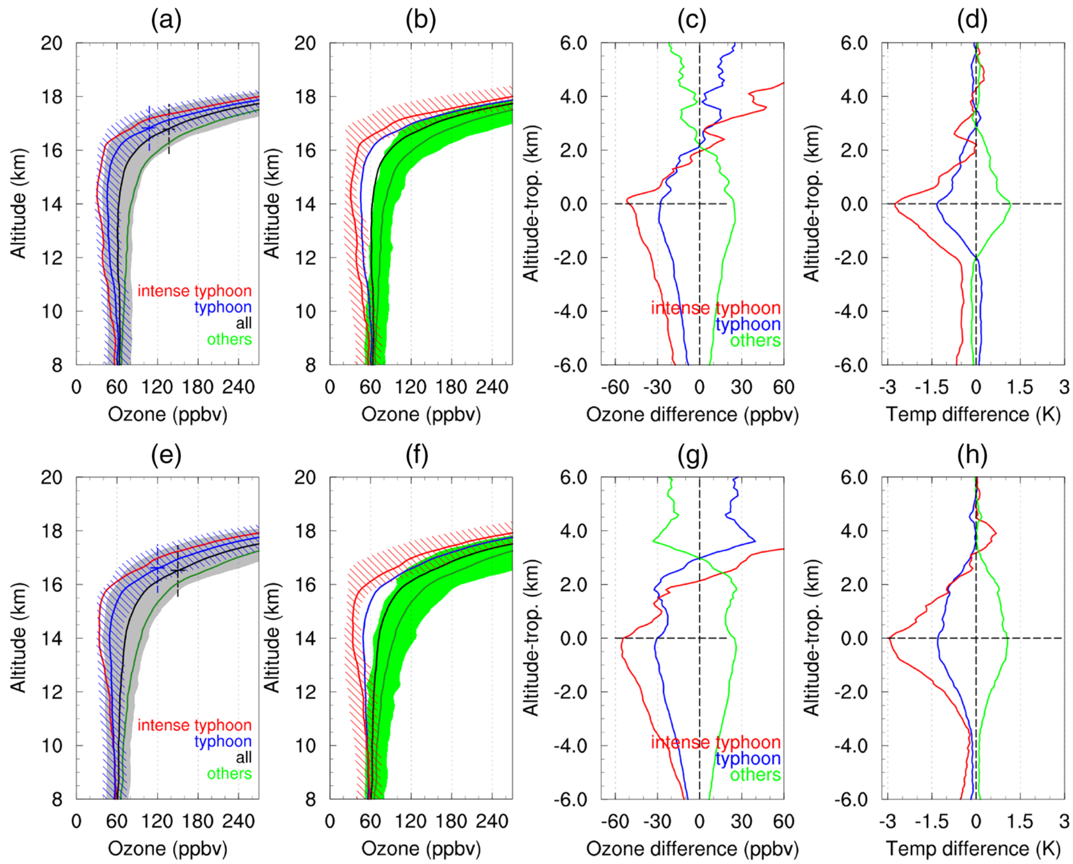

Figure 3. Mean ozone profiles with ± 1σ standard deviation for all (solid black, gray shaded), intense typhoon (red), normal typhoon (blue), and others such as stratospheric intrusions and transport from eastern China (green, green shaded) over (a and b) Hong Kong and (e and f) Naha. Ozone and temperature relative differences for intense typhoon (red line), typhoon (blue line), and others (green line) compared to mean ozone profile in (c and d) Hong Kong and (g), (h) Naha.

Figures 4b and 4d). The other pathway is from the top of a typhoon moving around the ASM anticyclone circulation and then arriving at Hong Kong and Naha after about 2 weeks (purple line in Figures 4b and 4d). During the long-range transport around the ASM anticyclone air parcels from the typhoon will be mixed with air from the ASM anticyclone before they reach Hong Kong and Naha.

Air parcels uplifted in a typhoon that are subsequently transported around the ASM anticyclone can maintain low ozone values for a period of about 2 weeks. As a result, balloon measurements in Hong Kong and Naha capture such ozone-poor air several days after the occurrence of a typhoon. This process constitutes an important transport pathway causing low ozone values as usually found within the ASM anticyclone. From the relative distribution function (Figure 4), we note that ozone values in Hong Kong are more strongly influenced by tropical cyclones than ozone valued in Naha. This is in apparent contrast with the tropical cyclone track distribution, which indicates that Hong Kong has a lower probability to be under the direct influence of tropical cyclones than Naha (Figure 1). The reason for this apparent contrast is that typhoon influence is also caused by the large-scale horizontal transport in the UTLS associated with the ASM anticyclone. Chemical reactions could also change the ozone concentrations in the UTLS, which are however not included in our CLaMS trajectory simulations. Air with low ozone originating from the western Pacific can be transported to Kunming, even to Lhasa or western Europe via the anticyclonic easterly flow of the ASM anticyclone (Li et al., 2017, 2020; Vogel et al., 2014).

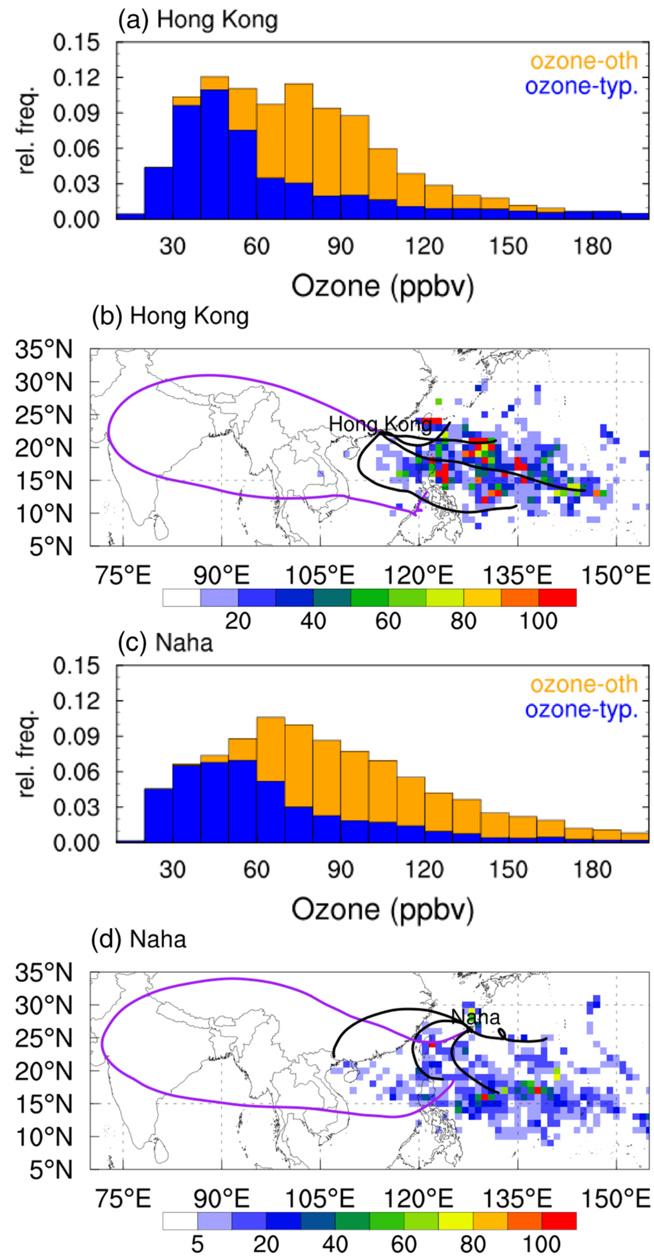

Figure 4. (a and c) The relative frequency distribution of measured ozone impacted by typhoons (blue) or by other processes such as stratospheric intrusions, air in the ASM anticyclone and advection transport from eastern China and the tropical region (orange) in the 12.5–17 km altitude range. (b and d) The color shows the number of trajectories for profiles with the negative ozone anomalies (<−20%), but the location is the point of strong uplift in the indicated latitude-longitude-box. The lines indicate some selected back-trajectories indicating the different transport pathways of air parcels from the location of the tropical cyclone to the measurement over Hong Kong and Naha (purple line, long-range transport around the ASM; black line, direct transport, for details see text). ASM, Asian summer monsoon.

Table 2
Numbers of Ozone Profiles Corresponding to Different Threshold for Ozone Anomalies for July-October From 2000 to 2017 in Hong Kong (Naha)

Ozone anomaly	−10%	−20%	−30%	−40%
Hong Kong	118 (48.4%)	113 (46.3%)	83 (34%)	41 (16.8%)
Naha	120 (45.3%)	119 (44.9%)	91 (34.3%)	50 (18.8%)

4. Conclusions

Ozone profiles recorded in Hong Kong and Naha between July and October in the years 2000–2017 are used for quantifying the impact of western Pacific typhoons on the variability of ozone in summer in the UTLS of South East Asia. Low-ozone values below 60 ppbv near the tropopause in Hong Kong and Naha are associated with strong vertical transport caused by tropical cyclones and the associated convection over the western Pacific. Our results indicate that 46.7% (44.9%) of ozone profiles are heavily impacted by tropical cyclones in Hong Kong (Naha) with negative ozone anomalies exceeding −20%, based on CLaMS trajectory calculations. Different thresholds for ozone anomalies are used to evaluate the cyclone's contribution (Table 2). A higher threshold (<−10%) has a minor impact on the conclusion compared to −20%, but the lower threshold (<−30%) results in a lower frequency of tropical cyclone's contribution (34%). Pairmary due to low threshold underestimated the cyclone's contribution. Intense typhoons affect 16.8% (18.8%) of the ozone profiles in Hong Kong (Naha) with larger negative anomalies (<−40%). In Hong Kong, the horizontal transport associated with the ASM anticyclone coupled with the vertical transport caused by tropical cyclones contributes significantly to the occurrence of low ozone values in the UTLS in the monsoon season. These findings are consistent with previous case studies (Li et al., 2017, 2020) analyzing the impact of a single typhoon. Tropical cyclones have the potential to reduce ozone by about 20–60 ppbv compared to average ozone values in the UTLS. Similar ozone reductions have also been seen in Hanoi (Thompson et al., 2012, their Figure 5a) in a region close to the tropics. We emphasize that the intensity and duration of tropical cyclones has been increasing in recent decades (Emanuel, 2005; Mei & Xie, 2016). Therefore, direct injections of ozone-poor air by rapid uplift in typhoons into the ASM anticyclone will likely increase in the future.

Data Availability Statement

Typhoons track data are download from http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html. Ozone data are obtained from https://woudc.org/data/explore.php?lang=en.

Acknowledgments
This work was partially supported by the National Key Research and Development Program of China (Grant No. 2018YFC1505703), the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA17010102), the National Natural Science Foundation of China (Grant Nos. 91837311, 41975050, and 41675040), the European Community's Seventh Framework Program (FP7/2007-2013) as part of the StratoClim project (Grant Agreement No. 603557), and the international Postdoctoral Exchange Fellowship Program 2017 under Grant No. 20171015.

References

Baray, J.-L., Ancellet, G., Randriambelo, T., & Baldy, S. (1999). Tropical cyclone Marlene and stratosphere-troposphere exchange. *Journal of Geophysical Research*, *104*, 13953–13970. https://doi.org/10.1029/1999JD900028

Bian, J., Li, D., Bai, Z., Li, Q., Lyu, D., & Zhou, X. (2020). Transport of Asian surface pollutants to the global stratosphere from the Tibetan Plateau region during the Asian summer monsoon. *National Science Review*, *7*, 516–533. https://doi.org/10.1093/nsr/nwaa005

Cairo, F., Buontempo, C., MacKenzie, A. R., Schiller, C., Volk, C. M., Adriani, A., et al. (2008). Morphology of the tropopause layer and lower stratosphere above a tropical cyclone: a case study on cyclone Davina (1999). *Atmospheric Chemistry and Physics*, *8*(13), 3411–3426. https://doi.org/10.5194/acp-8-3411-2008

Danielsen, E. F. (1993). In situ evidence of rapid, vertical, irreversible transport of lower tropospheric air into the lower tropical stratosphere by convective cloud turrets and by larger-scale upwelling in tropical cyclones. *Journal of Geophysical Research*, *98*, 8665–8681. https://doi.org/10.1029/92JD02954

Das, S. S. (2009). A new perspective on MST radar observations of stratospheric intrusions into-troposphere associated with tropical cyclone. *Journal of Geophysical Research*, *36*, L15821. https://doi.org/10.1029/2009GL039184

Das, S. S., Venkat Ratnam, M., Uma, K. N., Subrahmanyam, K. V., Girach, I. A., Patra, A. K., et al. (2016). Influence of tropical cyclones on tropospheric ozone: Possible implications. *Atmospheric Chemistry and Physics*, *16*(8), 4837–4847. https://doi.org/10.5194/acp-16-4837-2016

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*, 553–597. https://doi.org/10.1002/qj.828

Emanuel, K. (2003). Tropical cyclones. *Annual Review of Earth and Planetary Sciences*, *31*, 75–104. https://doi.org/10.1146/annurev.earth.31.100901.141259

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, *436*, 686–688. https://doi.org/10.1038/nature03906

Fu, Y. F., Xian, T., Lü, D. R., Liu, G. S., Heng, Z. W., Sun, L., et al. (2013). Ozone vertical variations during a typhoon derived from the OMI observations and reanalysis data. *Chinese Science Bulletin*, *58*(32), 3890–3894. https://doi.org/10.1007/s11434-013-6024-7

Fueglistaler, S., Legras, B., Beljaars, A., Morcrette, J.-J., Simmons, A., Tompkins, A. M., & Uppapla, S. (2009). The diabatic heat budget of the upper troposphere and lower/mid stratosphere in ECMWF reanalyzes. *Quarterly Journal of the Royal Meteorological Society*, *135*, 21–37. https://doi.org/10.1002/qj.361

Kobayashi, J., & Toyama, Y. (1966). On various methods of measuring the vertical distribution of atmospheric ozone (iii)–carbon iodine type chemical ozonesonde. *Paper in Meteorology Geophysics*, *17*, 113–126.

Komhyr, W. D., Barnes, R. A., Brothers, G. B., Lathrop, J. A., & Opperman, D. P. (1995). Electrochemical concentration cell ozonesonde performance evaluation during STOIC 1989. *Journal of Geophysical Research*, *100*(D5), 9231–9244. https://doi.org/10.1029/94JD02175

Konopka, P., Ploeger, F., & Müller, R. (2012). Entropy-based and static stability based Lagrangian model grids. In Lagrangian modeling of the atmosphere, Geophysical Monograph Series (Vol. 200, pp. 99–109). Washington, DC:American Geophysical Union.

Li, D., Vogel, B., Bian, J., Müller, R., Pan, L. L., Günther, G., et al. (2017). Impact of typhoons on the composition of the upper troposphere within the Asian summer monsoon anticyclone: the SWOP campaign in Lhasa 2013. *Atmospheric Chemistry and Physics*, *17*, 4657–4672. https://doi.org/10.5194/acp-17-4657-2017

Li, D., Vogel, B., Müller, R., Bian, J., Günther, G., Li, Q., et al. (2018). High tropospheric ozone in Lhasa within the Asian summer monsoon anticyclone in 2013: influence of convective transport and stratospheric intrusions. *Atmospheric Chemistry and Physics*, *18*(24), 17979–17994. https://doi.org/10.5194/acp-18-17979-2018

Li, D., Vogel, B., Müller, R., Bian, J., Günther, G., Ploeger, F., et al. (2020). Dehydration and low ozone in the tropopause layer over the Asian monsoon caused by tropical cyclones: Lagrangian transport calculations using ERA-Interim and ERA5 reanalysis data. *Atmospheric Chemistry and Physics*, *20*(7), 4133–4152. https://doi.org/10.5194/acp-20-4133-2020

Matsuura, T., Yumoto, M., & Iizuka, S. (2003). A mechanism of interdecadal variability of tropical cyclone activity over the western North Pacific. *Climate Dynamics*, *21*(2), 105–117. https://doi.org/10.1007/s00382-003-0327-3

Mei, W., & Xie, S. (2016). Intensification of landfalling typhoons over the northwest Pacific since the late 1970s. *Nature Geoscience*, *9*, 753–757. https://doi.org/10.1038/ngeo2792

Minschwaner, K., Manney, G. L., Petropavlovskikh, I., Torres, L. A., Lawrence, Z. D., Sutherland, B., et al. (2015). Signature of a tropical Pacific cyclone in the composition of the upper troposphere over Socorro, NM. *Geophysical Research Letters*, *42*, 9530–9537. https://doi.org/10.1002/2015GL065824

Newton, R., Vaughan, G., Hintsa, E., Filus, M. T., Pan, L. L., Honomichl, S., et al. (2018). Observations of ozone-poor air in the tropical tropopause layer. *Atmospheric Chemistry and Physics*, *18*(7), 5157–5171. https://doi.org/10.5194/acp-18-5157-2018

Pan, L. L., Homeyer, C. R., Honomichl, S. B., Ridley, B. A., Weisman, M., Barth, M. C., et al. (2014). Thunderstorms enhance tropospheric ozone by wrapping and shedding stratospheric air. *Geophysical Research Letters*, *41*, 7785–7790. https://doi.org/10.1002/2014GL061921

Pan, L. L., Honomichl, S. B., Randel, W. J., Apel, E. C., Atlas, E. L., Beaton, S. P., et al. (2015). Bimodal distribution of free tropospheric ozone over the tropical western pacific revealed by airborne observations. *Geophysical Research Letters*, *42*, 7844–7851. https://doi.org/10.1002/2015GL065562

Ploeger, F., Fueglistaler, S., Grooß, J.-U., Günther, G., Konopka, P., Liu, Y. S., et al. (2011). Insight from ozone and water vapor on transport in the tropical tropopause layer (TTL). *Atmospheric Chemistry and Physics*, *11*, 407–419. https://doi.org/10.5194/acp-11-407-2011

Ploeger, F., Konopka, P., Günther, G., Grooß, J.-U., & Müller, R. (2010). Impact of the vertical velocity scheme on modeling transport across the tropical tropopause layer. *Journal of Geophysical Research*, *115*, D03301. https://doi.org/10.1029/2009JD012023

Pommrich, R., Müller, R., Grooß, J.-U., Konopka, P., Ploeger, F., Vogel, B., et al. (2014). Tropical troposphere to stratosphere transport of carbon monoxide and long-lived trace species in the Chemical Lagrangian Model of the Stratosphere (clams). *Geoscientific Model Development*, *7*(6), 2895–2916. https://doi.org/10.5194/gmd-7-2895-2014

Randel, W. J., & Park, M. (2006). Deep convective influence on the Asian summer monsoon anticyclone and associated tracer variability observed with Atmospheric Infrared Sounder (AIRS). *Journal of Geophysical Research*, *111*, D12314. https://doi.org/10.1029/2005JD006490

Riese, M., Ploeger, F., Rap, A., Vogel, B., Konopka, P., Dameris, M., & Forster, P. (2012). Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects. *Journal of Geophysical Research*, *117*, D16305. https://doi.org/10.1029/2012JD017751

Schoeberl, M. R., & Dessler, A. E. (2011). Dehydration of the stratosphere. *Atmospheric Chemistry and Physics*, *11*(16), 8433–8446. https://doi.org/10.5194/acp-11-8433-2011

Schoeberl, M. R., Douglass, A. R., Zhu, Z. X., & Pawson, S. (2003). A comparison of the lower stratospheric age spectra derived from a general circulation model and two data assimilation systems. *Journal of Geophysical Research*, *108*(D3), 4113. https://doi.org/10.1029/2002JD002652

Thompson, A. M., MacFarlane, A. M., Morris, G. A., Yorks, J. E., Miller, S. K., Taubman, B. F., et al. (2010). Convective and wave signatures in ozone profiles over the equatorial Americas: Views from TC4 2007 and SHADOZ. *Journal of Geophysical Research*, *115*, D00J23. https://doi.org/10.1029/2009JD012909

Thompson, A. M., Miller, S. K., Tilmes, S., Kollonige, D. W., Witte, J. C., Oltmans, S. J., et al. (2012). Southern hemisphere additional ozonesondes (SHADOZ) ozone climatology (2005–2009): tropospheric and tropical tropopause layer (TTL) profiles with comparisons to OMI-based ozone products. *Journal of Geophysical Research*, *117*, D23301. https://doi.org/10.1029/2011JD016911

Thompson, A. M., Oltmans, S. J., Tarasick, D. W., von der Gathen, P., Smit, H. G., & Witte, J. C. (2011). Strategic ozone sounding networks: Review of design and accomplishments. *Atmospheric Environment*, *45*(13), 2145–2163. https://doi.org/10.1016/j.atmosenv.2010.05.002

Venkat Ratnam, M., Babu, S. R., Das, S. S., Basha, G., Krishnamurthy, B. V., & Venkateswararao, B. (2016). Effect of tropical cyclones on the stratosphere-troposphere exchange observed using satellite observations over the north Indian Ocean. *Atmospheric Chemistry and Physics*, *16*(13), 8581–8591. https://doi.org/10.5194/acp-16-8581-2016

Vogel, B., Günther, G., Müller, R., Grooß, J.-U., Hoor, P., Krämer, M., et al. (2014). Fast transport from Southeast Asia boundary layer sources to northern Europe: rapid uplift in typhoons and eastward eddy shedding of the Asian monsoon anticyclone. *Atmospheric Chemistry and Physics*, *14*(23), 12745–12762. https://doi.org/10.5194/acp-14-12745-2014