Observations of Large Ozone Losses over the Tropics

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Abstract: This paper reveals a new ozone hole that exists in the lower stratosphere over the tropics (30°N-30°S) across the seasons since the 1980s, where an ozone hole is defined as an area of ozone loss larger than 25% compared with the undisturbed atmosphere. The depth of this all-season tropical ozone hole is comparable to that of the well-known springtime ozone hole over Antarctica, while its area is about seven times that of the latter. At the center of the deepest tropical or Antarctic ozone hole, approximately 80% of the normal ozone value is depleted, whereas annual mean ozone depletion in the lower stratosphere over the tropics due to the coldest temperature is about 1.6 times that over Antarctica and is about 7.7 times that over the Arctic. The whole-year ozone hole over the tropics could cause a serious global concern as it can lead to increases in ground-level ultraviolet radiation and affect 50% of Earth's surface area, which is home to approximately 50% of the world's population. Moreover, since ozone loss is well-known to lead to stratospheric cooling, the presence of the all-season tropical ozone hole and the seasonal polar ozone holes is equivalent to the formation of three ‘temperature holes’ in the global lower stratosphere. These findings will play a far-reaching role in understanding fundamental atmospheric processes and global climate change.

Introduction

The Montreal Protocol and its revisions have successfully been executed, leading to the declining total level of halogenated ozone-depleting substances (ODSs) (mainly chlorofluorocarbons--CFCs) in the troposphere since around 1994. Yet, the 2020 ozone hole over the Arctic set a biggest record1, while the ozone hole over the Antarctic was one of the largest, deepest and most persistent ones in 2020 and the hole in 2021 is comparable to that in 2020. These observations are unexpected from the widely-accepted photochemical models2-6 but are in good accord with the prediction by the cosmic-ray (CR)-driven electron-induced-reaction (CRE) model7-9. The subject of this paper was motivated by the following observations and/or rationales. First, the author10 has recently demonstrated and quantitatively estimated that the CRE-initiated ozone-depleting reaction completely destroys or even overkills the ozone layer at the lower Antarctic stratospheric region at altitudes of 13.5-17.5 km corresponding to the CR ionization intensity maximum (the so-called Pfotzer maximum). Second, critically there exist all-season low-temperature cyclones centered at the altitude of around 15 km in the lower stratosphere over the tropics (30°N-30°S), in
which the CR ionization intensity peaks and the temperatures are low and comparable to that in the winter polar stratospheric vortex over Antarctica, just a little above that in the Antarctic but below that in the Arctic in winter. Remarkably, the annual mean lower stratospheric temperature over the tropics is the lowest, compared with those over the Antarctic and the Arctic, as will be shown later by data presented in this study. Third, cosmic rays being charged particles have a latitude effect due to the geomagnetic field, which leads to a maximum intensity in the polar stratosphere and a lower intensity by about 50% in the tropical stratosphere, whereas CFCs have a spatial distribution anti-correlated with the intensity of CRs (i.e., the concentrations of CFCs in the lower stratosphere over the tropics are approximately double those over the polar regions)\textsuperscript{8,11-13}. As mentioned in the above, the ozone holes over Antarctica\textsuperscript{14} and the Arctic\textsuperscript{15} have been well observed, whereas no ozone hole over the tropics has been reported. Reviewing the CRE mechanism deliberately\textsuperscript{11,13} and noticing the above-described observations, the author reached a hypothesis that there likely exists a large O\textsubscript{3} hole over the tropics, which should be comparable to the well-known Antarctic O\textsubscript{3} hole in depth and much larger than the latter in area. Therefore, this article is devoted to a search for the tropical ozone hole.

Despite the rationales described above, the search for the tropical O\textsubscript{3} hole is more challenging, compared with observations of the Antarctic and Arctic O\textsubscript{3} holes. This is due to some intrinsic challenges. First, unlike the polar O\textsubscript{3} holes that are seasonal and mainly appear in spring, an O\textsubscript{3} hole over the tropics if exists due to human-made gases is essentially unchanged across the seasons and is therefore hardly visible in original observed data. Second, unlike in the polar regions, the tropical O\textsubscript{3} layer mainly lies in the middle stratosphere (≥25 km) and a relatively smaller fraction (25-30%) of total ozone is distributed in the lower tropical stratosphere (at altitudes of 10-25 km). Thus, the amplitude of ozone depletion in the lower tropical stratosphere is less explicitly reflected in measured data of total ozone. An associated fact that led to no previous observations of any ozone hole over the tropics is the conventional definition of an ozone hole, which is defined as an area in which total ozone values drop below the historical threshold of 220 Dobson Units (DU). With this definition, no real tropical O\textsubscript{3} holes could be observed in satellite images of total ozone even if a large percentage of the O\textsubscript{3} amount in the lower tropical stratosphere is depleted. Moreover, much attention has been drawn to the studies of O\textsubscript{3} depletion over the polar regions, as no O\textsubscript{3} hole was expected to appear over the tropics from current photochemical models. Thus, satellite observations were mainly focused on the polar O\textsubscript{3} holes and originally observed data were
often pre-processed under the assumption that “any significant departures from photochemical equilibrium are the result of bulk air motions” in the troposphere and stratosphere. Fortunately, ground-based measurements since the 1950s combined with satellite measurements since 1979 of ozone, CFCs and temperature in the stratosphere still provide sufficient data to examine the above hypothesis. Here an ozone hole is defined as an area with ozone loss in percent larger than 25%, with respect to the normal/undisturbed value when there were no significant CFCs in the stratosphere (approximately in the 1960s). Despite its difference from the conventional definition of an O₃ hole, this new definition is supported by the observed O₃ loss (~25% in spring) over the Arctic (shown later) where and when an O₃ hole was reported. In other words, an area with O₃ loss values by 25% is approximately the threshold of observing an Arctic O₃ hole.

Results and Discussion

(I) Ozone climatology. A standard troposphere-stratosphere climatology in altitude relative to the ground level in the Trajectory-mapped Ozoneonde dataset for the Stratosphere and Troposphere (TOST) obtained from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) is used for the present study. TOST is a global 3-D (latitude, longitude, altitude) climatology of tropospheric and stratospheric ozone, derived from the WOUDC global ozone sounding record by trajectory mapping and uses approximately 77,000 ozonesonde profiles from some 116 stations worldwide since 1965. In TOST, ozone measurements were mapped at 1-km altitude intervals, with details given by Liu et al\(^{16}\). The long-term zonal mean latitude-altitude distribution of the ozone climatology measured over the past five decades (1960s-2010s) are shown in Figure 1.

![Figure 1](image)

Figure 1. Long-term zonal mean latitude-altitude distribution of the ozone climatology averaged from 1960s to 2010s.
To reveal the tropical ozone hole, we show the differences of the ozone climatology in 1970s, 1980s, 1990s, 2000s and 2010s with respect to that in 1960s. It is important to note that the distribution of ozone over the tropics is highly ununiform in altitude. Thus, the differences in zonal mean latitude-altitude distribution of the ozone climatology do not simply reflect the value of ozone depletion by a physical mechanism, and there are larger ozone losses in absolute values in higher altitudes in the lower tropical stratosphere. According to the equation derived from the CRE mechanism, the relative ozone change in percent in a potential ozone hole is given by\textsuperscript{11-13}:

\[
\frac{\Delta [O_3]}{[O_3]_0} = k [C]^2,
\]

where \([O_3]_0\) is the normal ozone amount when there were no significant CFCs present in the stratosphere (i.e., \([O_3]_0 = [O_3]\) in the 1960s), \([C]\) is the equivalent effective chlorine (EECI) in the stratosphere, \(I\) is the CR intensity, and \(k\) is a fitting constant determined by the best fit to past measured O\(_3\) data. Thus, we plot the relative ozone changes in percent in 1970s-2010s with respect to that in the 1960s when there were no significant effects from CFCs. Moreover, the large Antarctic ozone hole is well known to appear in the spring season, while the hypothesized ozone hole over the tropics is expected to appear in all four seasons. Thus, we first show the observed results for the Antarctic spring season (September, October and November—SON) in order to compare the well-known Antarctic O\(_3\) hole with the tropic ozone hole if exists. The thus plotted results show that from the 1960s to the 1970s (see Figure S1), there were almost no ozone holes but small ozone decreases at 10-20 km over the Antarctica and at 16-25 km over the tropics and there was a tropospheric-stratospheric zone of significant ozone increases at altitudes below 16 km and latitudes of 10°N-40°S, which was likely caused by volcanic effects. The small O\(_3\) decreases in the lower polar and tropical stratospheres are expected, as it is known that the reaction of stratospheric CFCs remained insignificant up to the 1970s. In contrast, the observed results for the 1980s-2010s plotted in Figure 2 clearly show that along with the well-known Antarctic ozone hole, a deep and large ozone hole with ozone loss up to 50% over the tropics started to appear in the 1980s. The Antarctic hole reached the largest and deepest in the 1990s, while the tropic hole continued to grow and deepen in the 1990s and reached its maximum in the 2000s. For both largest and deepest Antarctic (1990s) and tropic (2000s) ozone holes, the same maximum (decadal averaged) ozone loss of approximately 80% at the centers of both holes was observed. However,
it is worthwhile to note that the geometric area of the tropical ozone hole at latitudes of 30° S-30° N is approximately 7.5 times that of the Antarctic hole at 60°-90° S. Both holes in the 2010s were slightly smaller than those in the 2000s.

**Figure 2.** Relative changes in percent of the ozone climatology in the season SON of the 1980s, 1990s, 2000s and 2010s with respect to that in the 1960s.

To show the relative ozone changes in the Antarctic, tropical and Arctic stratospheres over the seasons, the differences of the ozone climatology in the 2000s with respect to that in the 1960s for SON, DJF (December, January and February), MAM (March, April and May), and JJA (June, July and August) are plotted in Figure 3. As expected, the polar ozone holes have strong seasonal variations and mainly appear in their respective spring season (SON for the Antarctica and MAM for the Arctic), whereas the tropical ozone hole shows a weak sensitivity to seasons with the slightly largest and deepest hole in the season of DJF due to a little colder tropical stratosphere in this season (see the temperature data shown later). The Arctic ozone hole in MAM with a maximum ozone loss of ~25% is far less and smaller in both depth and area than the Antarctic hole.
in SON or the tropical hole in any season. This is not unexpected, as the winter and spring stratosphere of the Arctic is well known to be much warmer than that of the Antarctic or the tropics and the Arctic polar vortex is not as well formed and as persistent as in the Antarctic or tropics.

Figure 3. Relative changes in percent of the ozone climatology in the seasons DJF, MAM, JJA and SON of the 2000s with respect to that in the 1960s.

To show the time-series depths of the decadal mean Antarctic, Arctic and tropical ozone holes in SON, MAM and annual respectively, averaged ozone changes in percent at the lower stratospheric altitudes of 14-21 km are shown in Figure 4, which also includes the data for the sum of concentrations of main ODSs (CFCs and CCl4) measured in the troposphere (no transport lag times considered). It is interesting to show quantitatively that the Antarctic ozone hole reached its maximum loss by about 60% in the 2000s, whereas the tropical hole reached its maximum loss by about 56% in the 2000s. The appearance of the deepest Antarctic hole in the 2000s in Figure 4 is slightly different from that appearing in the 1990s in Figure 2. This difference is due to the
significant penetration of the Antarctic hole into the lower stratosphere at 10-14 km. Thus, the largest/deepest Antarctic ozone hole should have occurred in the 1990s, as more truly shown in the image of Figure 2. By contrast, the Arctic ozone hole reached its maximum loss by 20-25% in 1990s-2010s, less than the half of the maximum loss in the Antarctic or tropical hole.

![Graph showing ozone changes](image)

**Figure 4.** Time-series decadal mean ozone changes in percent with respect to that of the 1960s at the lower stratosphere of 14-21 km of the Antarctic in SON, the Arctic in MAM and the all-season (annual) tropical (solid lines in black) and time-series sum of concentrations of main ODSs (CFCs and CCl4) measured in the troposphere (no transport lag times considered) (solid circles in red) from the 1960s to the 2010s.

At the first glance, the mean depth of the tropical ozone hole with a maximum ozone loss of ~56% being close to that of the Antarctic ozone hole with a maximum ozone loss of ~60% appears surprising. Since the lower stratospheric temperature over the tropical over the seasons is close to that in the Antarctic polar vortex and the CR ionizing rate and the CFC concentrations in the lower stratosphere over the Antarctic are respectively 2-3 and 1/2-2/3 times those over the tropics, the observed results in Figure 4 appear to deviate from the quadratic dependence of ozone loss on the CR intensity expressed in Eq. (1). However, the author10 has recently demonstrated that the ozone
layer in the CR-peak region at altitudes of 13.5-17.5 km is completely depleted (overkilled) in the deepest Antarctic ozone hole, leading to its less sensitivity to the variation of the CR intensity. This can fairly explain the observed relatively smaller ozone depletion ratio of the Antarctic to the tropical ozone hole than expected from Eq. (1).

(II) CFC-12 distribution. The author\textsuperscript{11-13} has previously shown that significant decompositions of CFCs and N\textsubscript{2}O but not CH\textsubscript{4} occur in the lower stratosphere over Antarctica during winter, using the NASA UARS and ESA’s MIPAS satellite datasets of the 1990s and the 2000s respectively. The data provided solid evidence of the CRE reactions of CFCs and N\textsubscript{2}O, but not CH\textsubscript{4}, in the \textit{winter} polar stratosphere, though CH\textsubscript{4} is not even a secure ‘inert trace gas’ because it can also react with radicals generated from the CRE reactions of CFCs or N\textsubscript{2}O. Correspondingly, the observed ozone data also showed significant ozone depletion over Antarctica in the JJA, which was not explainable by any photochemical models due to the lack of sunlight in the lower polar stratosphere in the JJA. The real-time variation of total O\textsubscript{3} closely following that of CFCs or N\textsubscript{2}O during the winter season indicated that the CRE mechanism played an important role in causing the observed O\textsubscript{3} loss over Antarctica. The CRE mechanism can lead to the formation of reactive halogen species to destroy ozone in both the \textit{winter} polar stratosphere in darkness and the \textit{springtime} polar stratosphere with sunlight. This is in fact confirmed again with the observed latitude-altitude distribution of the ozone climatology over the four seasons shown in Figure 3.

Here zonal mean latitude-altitude distribution of CF\textsubscript{2}Cl\textsubscript{2} (CFC-12) in 1992 from the dataset of the NASA UARS (CLEAS), which was one of the most accomplished satellites in atmospheric science, together with the relative difference averaged over the seasons of the ozone climatology in the 1990s with respect to that in 1960s, is plotted in Figure 5. Note that the satellite dataset for CFC-12 only covered the stratosphere at altitudes above 16 km. The CFC-12 images over the four seasons are shown in Figure S2 in Supplementary Information. The data clearly show the depletion of CFC-12 in the winter and early spring lower polar stratosphere, as observed previously\textsuperscript{11-13}. Most important information drawn from the data in Figure 5, which has never been found previously, is that in all seasons, the CFC-12 concentration was depleted in the lower stratosphere below 25 km over the tropics (at latitudes of 30°S-30°N), most significant in the zone below 20 km and at 20°S-20°N, where the largest tropical ozone hole is located. It is well known that below 20 km, the photodissociation rates of CFCs are negligibly small.
A critical aspect of information implied in the observed data in Figures 2-5 is that, like the Antarctic ozone hole that cannot be explained by the once misconceived air transport mechanism (‘dynamical theory”), the tropical ozone hole must not result from any changes in normal atmospheric circulation patterns over the tropics since the 1960s-1970s. The latter does not agree with the following observations. First, the tropical ozone hole is closely dependent on the atmospheric level of CFCs (Figure 4), so it must originate from a CFC-related mechanism. Second, one might be attempted to link the tropical ozone hole with the postulated stratospheric cooling effect of increasing non-halogenated greenhouse gases (CO₂, CH₄ and N₂O), which was not seen in observed ozone and temperature data for the lower Antarctic stratosphere over the past 4-5 decades. Obviously, such a greenhouse effect would have resulted in a continuous shift in the altitude position of the tropical or Antarctic ozone hole; on the contrary, the observed data robustly show no shifts in the positions of both Antarctic and tropical ozone holes that have constantly been centered at the altitude region around the maximum CR ionization intensity since the 1960s.
(Figures 2 and 3). Third, critically the ‘dynamical theory’ (any increased upward motion of ozone-poor air) contradicts with the observation of CFC depletion in the lower tropical stratosphere as increased upward motion would transport CFC-rich air from the troposphere (Figure 5). Fourth, any changes in atmospheric circulation patterns to enhance air upward motions with respect to the normal undisturbed tropics would not lead to the formation of circularly symmetric ozone depletion cyclones with the largest depletion at the center that is located at the CR ionization peak position. Finally, one might also be attempted to explain the observed tropical ozone hole as a result of the Antarctic ozone hole changing the normal atmospheric circulation patterns over the tropics. This explanation cannot be correct either, as the Antarctic ozone hole is seasonal and appears only in the springtime, whereas the tropical ozone hole is all-season and has no changes in its center location over the seasons and over the decades since its significant appearance in the 1980s. Although one might make various arguments, the depletion of both CFCs and ozone in the lower stratosphere is most likely due to a physical reaction mechanism that occurs locally. For the latter, the CRE mechanism, supported by the data presented in Figures 1-5 above and other figures to be present below as well as previous analyses of substantial datasets obtained from both laboratory and atmospheric measurements, provides a reasonable and predictive candidate.

(III) Time-series total ozone, Ozoneonde and Umkehr datasets. Time-series total ozone data at the springtime Antarctic (60°-90°S) and the annual tropics (30°S-30°N) measured by satellites since the 1979 obtained from NASA and WOUDC are shown in Figure 6, whereas the Umkehr dataset for the Mauna Loa (19.5°N, 155.6°W, HI, USA) obtained from NOAA and WOUDC is shown in Figure 7. From Figure 6, it is seen that the decreases in absolute total ozone values over the tropics are smaller than those over the Antarctic. This is expected due to the difference between the undisturbed ozone distributions over the Antarctic and the tropics, as mentioned in the above. The 11-year cyclic variation of total ozone over Antarctica has been well reported and reproduced by the CRE equation previously\textsuperscript{11-13}. Note that the overkilling effect of the CRE mechanism in the CR-peak stratospheric layer should be less significant in total ozone data as the partial total ozone in the stratospheric layer at altitudes of 13.5-17.5 km takes only a fraction of total ozone over the Antarctic. Thus, we might as well use the CRE Eq. (1) to give a quantitative analysis of the observed data. Given the observed distributions of the CR ionization rate and CFCs versus latitude and the use of the CR intensity at the Antarctic and the concentrations measured at the lower
Figure 6. Time-series total ozone at the springtime Antarctic (60°S-90°S) and the annual tropics (30°S-30°N) measured by satellites since the 1979, as well as the fitted curve (thick solid line in green) given by the CRE equation (for details, see text). Also shown are the 3-year smoothing (thick solid line in red) to the observed data.

troposphere of CFCs which are well mixed globally as inputs to calculate ozone loss over both the Antarctic and the tropics, the reaction constant $k$ in Eq. (1) for the Antarctic is approximately double that for the tropics, i.e., $k_{Tro} \approx \frac{1}{2} k_{Ant}$. Another factor must also be considered, that is, the transport lag times of CFCs from the troposphere (surface) to the lower stratosphere over the Antarctic and the tropics, which are about 1 year and 10 years respectively determined from previous analyses of the observed data in terms of the CRE reaction mechanism$^{10-13}$. Moreover, we make a rough and simplified assumption that only the ozone layer in the lower stratosphere below 25 km (i.e., ~25% of the total ozone value) over the tropical is depleted by the CRE mechanism. Taking all these factors into account, the modeled results from the CRE mechanism are shown in Figure 6. It is seen that given the fluctuation level of observed data, the results fitted
by Eq. (1) for the Antarctic ozone hole are excellent. This gives rise to the best fitting constant $k_{Ant}$, half value of which ($k_{Trop} \approx \frac{1}{2} k_{Ant}$) is used to calculate the ozone loss over the tropics without further adjustment. We notice that the modeled results for ozone loss over the tropics is not as good as that for the Antarctic. Given that several rough approximations are made in this modeling, the modeled results reproduce the observed data reasonably well and are able to capture the main characteristic of the 11-year cyclic variation. Keep in mind that the relationship of $k_{Trop} \approx \frac{1}{2} k_{Ant}$ will also be used to model the lower stratospheric temperatures as a result of ozone depletion over the Antarctic and the tropics below.

**Figure 7.** Time-series Umkehr data of annual mean vertical distribution partial column ozone at the lower and upper stratospheric layers (63-32 hPa and 8-4 hPa) at Mauna Loa (19.5°N, 155.6°W, HI, USA). Also shown are the 5-year smoothing (thick solid line in red) to the observed data.

For the Antarctic ozone hole, the 11-year cyclic oscillation of total ozone was mainly due to the CRE-caused ozone loss in the stratospheric layers at which the CR ionization intensity was strong, with the most pronounced effect at the Umkehr layer of 63-32 hPa (21-25 km) slightly above the CR-peak layer of 126-63 hPa (15-21 km) in which the CRE mechanism overkilled the ozone layer. In contrast, no 11-year cyclic variations were observed for ozone in the upper
stratospheric layer where the photochemical mechanism dominates\textsuperscript{10}. A similar behavior is now observed for ozone loss over the tropics, as shown in Figure 7. The results in Figures 6 and 7 confirm that ozone depletion over the Antarctica and the tropics must arise from an identical physical mechanism. So far, the CRE mechanism is the only physical mechanism that gives rise to the observed 11-year cyclic ozone or temperature variations in the lower stratosphere\textsuperscript{10}.

**(IV) Lower stratospheric temperature.** It is well known that O\textsubscript{3} depletion causes stratospheric cooling\textsuperscript{17,18}; temperature drop in the lower polar stratosphere is a direct measure of O\textsubscript{3} loss. The author has well demonstrated that over the Antarctic, the lower stratospheric temperature regulated by stratospheric cooling due to O\textsubscript{3} loss has a pronounced 11-year cyclic variation and can be well reproduced by the CRE equation\textsuperscript{10-13}. Figure 8 shows time-series temperature anomaly datasets at the lower stratospheres (100-30 hPa) over the Antarctic and the tropics from multiple satellite and ground-based measurements, including NOAA’s Microwave Sounding Units (MSU) UAH\textsuperscript{19} and RSS\textsuperscript{20} satellite datasets (Channel 4), ROM SAF’s radio occultation (RO) satellite datasets, and NOAA’s radiosonde-based Ratpac-B time-series dataset\textsuperscript{21} that was based on data from 85 weather balloon stations distributed around global land areas and recommended by NOAA for assessing long-term changes in tropospheric and lower stratospheric temperatures on large spatial scales. These datasets for the Antarctic solidly confirm the 11-year cyclic lower stratospheric temperature variation reported previously\textsuperscript{10-13}, while the lower stratospheric temperature over the tropics generally shows a similar cyclic variation. In modeling the lower stratospheric temperatures, we use the same relationship of $k_{Tro} \approx \frac{1}{2} k_{Ant}$ as that used for modeling the ozone data in Figure 6. It is seen that the CRE equation can fit to the observed temperature data reasonably well, even though the latter are obtained from multiple data sources.
Figure 8. Time-series annual mean lower stratospheric temperature anomaly datasets of the Antarctic and the tropics since 1960, obtained from multiple ground- and satellite-based data measurements (Ratpac, MSU-UAH, MSU-RSS and ROM SAF), as well as the fitted temperatures given by the CRE equation (see text). Also shown are the 3-year smoothing (thick solid lines in colors) to the observed temperature anomalies (symbols). Note that the datasets had various reference temperatures and had therefore to be offset to match the Ratpac dataset that has covered the longest observation time (1958-present), but this offsetting has no effects on the long-term trends.

Furthermore, a high-quality dataset of the seasonal zonal mean latitude-altitude distribution of the temperature at altitudes of 0-50 km for 2002-2010, which is made from the zonally averaged monthly means on a latitude-altitude grid of RO data from the Metop, Sentinel-6 and Metop-SG satellites and RO data from other missions, obtained from the ROM SAF, is shown in Figure 9. The ROM SAF’s reprocessed Climate Data Record (CDR) dataset, providing a higher degree of homogeneity of the RO data sets, is used for the current study. Remarkably, the data show that the temperature in the low-temperature cyclones over the tropics over the seasons is 6-8 K higher than that in the Antarctic polar vortex in winter (JJA) but 11-13 K below that in the Arctic polar vortex.
in winter (DJF). This can well explain why the ozone hole over the Antarctic or tropics is much larger and deeper than the Arctic ozone hole and why the tropical ozone hole is constantly formed over the seasons. The annul mean zonal mean latitude-altitude distribution of the temperature averaged over the four seasons is shown in Figure 10. The latter shows a remarkable phenomenon that the annul mean lower stratospheric temperature over the tropics is the lowest at 193-198 K, compared with 209-216 K over the Antarctic and 217-220 K over the Arctic. Correspondingly, the annul mean O₃ depletion is the largest in the tropical O₃ hole (Figure 5), which is 77% versus 47% for the Antarctic and versus ~10% for the Arctic in the 1990s when the polar holes peaked.

**Figure 9.** Seasonal zonal mean latitude-altitude distribution of the temperature climatology in the troposphere and stratosphere in the 2000s (averaged from 2002 to 2010).
Figure 10. Annual mean zonal mean latitude-altitude distribution of the temperature climatology in the troposphere and stratosphere in the 2000s (averaged from 2002 to 2010).

It is well known that polar stratospheric clouds (PSCs) that form in the polar night regions of the stratosphere are crucial for formation of the Antarctic ozone hole. It was proposed that on the surfaces of PSCs, chlorine reservoir molecules (HCl and ClONO$_2$) are converted into photoactive forms (Cl$_2$) that can then undergo photolysis to destroy ozone$^{4-6}$. There are two types of PSCs, namely Type I and Type II PSC. The composition of Type II PSC is water ice, while Type I PSC is composed of mixtures of nitric acid (HNO$_3$), water vapor (H$_2$O), and sulfuric acid (H$_2$SO$_4$). The temperatures required for formation of Type I and II PSCs are 195K and 188K, respectively. Thus, it is very likely that tropical stratospheric clouds (TSCs), at least Type I-like TSCs, can also form in the lower tropical stratosphere over the seasons. It is important to note that the lower tropical stratosphere is very different from the lower polar stratosphere in compositions. The former is rich of CFCs, whereas the latter is composed of lower-level CFCs and inorganic chlorine (HCl and ClONO$_2$). However, the CRE mechanism has proposed the ozone-depleting reactions of both CFCs and inorganic chlorine species on the surfaces of PSCs for the past two decades$^{10-13}$. Therefore, there are required and sufficient conditions for ozone-depleting reactions to occur on the surfaces of proposed TSCs in the lower tropical stratosphere over the four seasons.

Another important result is that the global lower stratospheric temperature is essentially governed by the ozone layer, which is expected as ozone is the main and dominant molecule that
absorbs solar radiation in the stratosphere. As a result, the presence of the three ozone holes will play a major role in stratospheric cooling and regulating the global lower stratospheric temperature, as seen previously\textsuperscript{10-13} and in the results shown in Figures 8-10. This is equivalent to the formation of three ‘temperature holes’ corresponding to the Antarctic, tropical and Arctic ozone holes respectively. This key conclusion will be further explored in the subsequent paper.

Conclusions

A critical review of the CRE mechanism led to a hypothesis of an ozone hole in the lower stratosphere over the tropics. Substantial datasets of troposphere-stratosphere ozone climatology since the 1960s, latitude-altitude CFC distribution, time-series total ozone, Ozonesonde and Umkehr datasets, lower stratospheric temperature climatology from multiple ground-based or satellite measurements provide strong evidence of the existing whole-year ozone hole over the tropics. At the hole center, up to approximately 80\% of the ozone concentrations relative to the normal value in the 1960s is depleted. The averaged depth of the annual tropic ozone hole is comparable to that of the springtime Antarctic ozone hole, while the size of the tropic hole is about seven times that of the Antarctic hole. The annul mean ozone depletion in the lower stratosphere over the tropics is strikingly large, which is 77\% versus 47\% over the Antarctic and versus ~10\% over the Arctic in the 1990s when the polar holes were in their peaks. The lower tropical stratosphere is rich of CFCs and CR ionization events, and critically its temperature for all seasons is sufficiently cold for formation of PSC-like TSCs. Therefore, there is every reason to conclude that the CRE mechanism of ozone-depleting reactions have most likely taken place on the surfaces of TSCs present in the lower stratosphere over the tropics, leading to the formation of the tropical ozone hole in the whole year.

The tropics (30°N-30°S) constitutes 50\% of Earth's surface area, which is home to about 50\% of the world's population. Ozone depletion in the tropics could cause a large global concern. In areas where ozone depletion is observed to be smaller in absolute ozone value, UV-B increases are more difficult to detect as detection of UV-B trends associated with ozone loss can be complicated by changes in cloudiness, local pollution, and other difficulties. However, it is generally agreed that the depletion of the ozone layer leads to an increase in ground-level UV radiation (especially UV-B) because ozone is an effective absorber of solar UV radiation. Exposure to enhanced UV-B levels could increase the incidence of skin cancer and cataracts in
humans, weaken human immune systems, decrease agricultural productivity, and negatively affect sensitive aquatic organisms and ecosystems\textsuperscript{22}. In fact, there are reports of an "ozone mini hole" over the Tibetan Plateau (Xizang, China, 29.6° N, 91.1° E) at times with colder winters\textsuperscript{23,24}, which is located at the edge of the tropics. Moreover, there was a report called HIPERION published by the Ecuadorian Space Agency in 2008\textsuperscript{25}. The study using ground measurements in Ecuador and satellite data for several countries over 28 years found that the UV radiation reaching equatorial latitudes was far greater than expected, with the UV Index as high as 24 in Quito. This Ecuadorian report concluded that ozone depletion levels over equatorial regions are already endangering large populations in the regions. Further studies of ozone depletion and UV radiation change in the tropical regions will be of great interest and significance.

On the global scale, the presence of the Antarctic, tropic and Arctic ozone holes seriously affect the climates of the stratosphere and the surface. Stratospheric cooling is a well-known direct consequence of ozone depletion. Distinguishing this result from the proposed stratospheric cooling caused by increased non-halogenated greenhouse gases (CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O) is of great importance to understanding global climate change. As far as observed ozone and temperature data in the stratosphere since the 1950s or 1960s are concerned, as shown in the present study and previous studies\textsuperscript{10-13}, there seems no or little observed evidence of the stratospheric cooling effect of these non-halogen greenhouse gases. This critical conclusion certainly requires further scrutiny, which will be the subject of a subsequent paper.

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\textbf{AUTHOR DECLARATIONS}

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