LETTERS

502.3 : 551.510.534 (99)

SPLITTING OF OZONE HOLE OVER ANTARCTICA ~ ITS EFFECT ON TOTAL COLUMN OZONE AND ITS POSSIBLE CAUSES

1. Ozone is a minor constituent of the atmosphere. About 90% of the total ozone is found in the stratosphere from approximately 10 km to 50 km above the surface of the Earth (Kowalok, 1993), with a maximum concentration around 25 km altitude (Ghosh and Midya, 1994). The rest 10% of the total ozone is distributed in the troposphere and upper atmosphere. The total column ozone indicates both the tropospheric as well as stratospheric ozone over a specified region. Ozone plays an important role in the chemical kinetics of different ionospheric radiations (kvifte, 1973; Midya et al., 2001). Stratospheric ozone plays an important role in protecting the Earth’s surface against the harmful solar ultraviolet radiation (mainly UV-B) and controlling the temperature structure of the stratosphere (Ghude et al., 2005). Ozone also influences cyclonic disturbances and other tropospheric phenomenon also (Mitra, 1992; Midya et al., 2012).

It has been reported that ozone in the stratosphere is declining everywhere by smaller amount (Bojkov, 1992). The term ozone hole is applied to the regions where ozone depletion is severe and the level fall below 200 DU. In normal, ozone concentrations is about 300 to 350 DU. The annual thinning of ozone layer over Antarctica, during the polar spring time, was first reported by Farman et al., 1985. Evidence of dramatic year to year decline in total ozone over Antarctic spring has also been reported (Schoeberl and Krueger, 1986). The total ozone over Antarctica has declined by 33%, integrated ozone between 14 km and 18 km by more than 70% while within the polar vortex ozone suffer depletion by more than 90% (Hofmann et al., 1987). It has been confirmed that depletion of ozone over Antarctica starts from late August and reaches its minimum in mid October (Gardiner, 1988). Afterwards, verified by different investigators throughout the world (Jones and Shanklin, 1995; Midya and Jana, 2002; Sivasakthivel and Reddy, 2011).

Different theories are proposed for the dramatic decrease of ozone concentration over Antarctica during spring time.

(i) Chemical theory: There are different chemicals such as O₃ (Chapman, 1930), HO₃ (Thompson, 1992), Cl, and ClO₃ (Molina and Rowland, 1974; Molina and Molina, 1987), Br and BrO₃ (Wofsy et al., 1975; Fan and Daniel, 1992), ClO₃ and BrO₃ (McElroy et al., 1986), NO₃ (Crutzen and Arnold, 1986; Andreae and Crutzen, 1997) etc. which undergo different chemical reactions hence are responsible for depletion of ozone.

It is proposed that the formation of ozone hole is due to catalytic depletion of ozone caused mainly by Cl radical from photolysis of CFCs on the surface of polar stratospheric clouds (PSC) (Toon and Turco, 1991; Fahey et al., 1989).

(ii) Natural theory: Natural phenomenon associated with solar cycle and radiations from sun are responsible for ozone depletion (Bekki et al., 1991).

(iii) Dynamical theory: According to this theory, ozone is not depleted but distributed in the atmosphere; as a result, ozone hole is created (Jana and Nandi, 2005).

From research it has been found by several investigators that the Antarctica’s ozone hole has shrunk into its smallest size (Newman, 2002) since 1988 and split into two pieces in 2002. Varotsos, 2003 explained that extremely large amplitude of planetary wave present breaks the Antarctic ozone hole in two small holes. The splitting of ozone hole attracts many scientists to work on this topic (Varotsos, 2002). It is also reported that the southern hemisphere polar stratosphere during September 2002 was characterized by the occurrence of an unprecedented major stratospheric warming (Varotsos, 2004; Savigny et al., 2005).

Though several works on ozone depletion, ozone hole formation and ozone hole splitting, over Antarctica have been already done by several researchers, the long term effect of ozone hole splitting over Total Column Ozone (TCO) is still a topic of interest. The purpose of this paper is to check whether there is a change in long term TCO trend over Antarctica before and after the splitting of the ozone hole on 2002.

2. Satellite observational data of total column ozone for the Antarctic stations, Halley Bay and South Pole Observatory (SPO) is taken for the analysis. To check the effect of ozone hole splitting, the

TABLE 1

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
<th>Time from UTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halley Bay</td>
<td>75° 60' S</td>
<td>26° 21' W</td>
<td>30 m</td>
<td>-2 hours</td>
</tr>
<tr>
<td>South Pole</td>
<td>89° 98' S</td>
<td>24° 80' W</td>
<td>2810 m</td>
<td>+12 hours</td>
</tr>
<tr>
<td>Perth</td>
<td>31° 51' S</td>
<td>115° 96' E</td>
<td>5 m</td>
<td>-8 hours</td>
</tr>
<tr>
<td>Mauna Loa</td>
<td>19° 53' N</td>
<td>155° 57' W</td>
<td>3397 m</td>
<td>-10 hours</td>
</tr>
<tr>
<td>Wallops Island, Virginia</td>
<td>37° 86' N</td>
<td>76° 51' W</td>
<td>13 m</td>
<td>-5 hours</td>
</tr>
<tr>
<td>Tutuila</td>
<td>14° 24' S</td>
<td>170° 56' W</td>
<td>42 m</td>
<td>-11 hours</td>
</tr>
</tbody>
</table>

years 1992-2001 are chosen as the period before splitting of the ozone hole and the years 2003-2014 are considered as the period after splitting of the ozone hole. To support the observations, the Ozone Depleting Substances (ODS), O¹⁸/O¹⁶ ratio in CO₂ data are analyzed. Satellite data of TCO over few stations near Antarctica are also taken for analysis. The data of total column ozone, ODS, and O¹⁸/O¹⁶ ratio in CO₂ are taken from [http://www.esrl.noaa.gov/gmd/dv/data/](http://www.esrl.noaa.gov/gmd/dv/data/). The stations taken for analysis are Perth, Mauna Loa, Wallops Island and Tutuila. Details about these stations are presented in Table 1.

TABLE 2

<table>
<thead>
<tr>
<th>Chemical name</th>
<th>Lifetime (yrs)</th>
<th>ODP (WMO 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC-11 (CCl₃F) Trichlorofluoromethane</td>
<td>45</td>
<td>1</td>
</tr>
<tr>
<td>CFC-12 (CCl₂F₂) Dichlorodifluoromethane</td>
<td>100</td>
<td>0.82</td>
</tr>
<tr>
<td>CFC-113 (C₂F₃Cl₃) 1, 1, 2 Trichlorotrifluoroethane</td>
<td>85</td>
<td>0.85</td>
</tr>
<tr>
<td>Methyl Chloroform (C₂H₃Cl₃) 1, 1, 1 trichloroethane</td>
<td>5</td>
<td>0.16</td>
</tr>
<tr>
<td>CCl₄ Carbon tetrachloride</td>
<td>26</td>
<td>0.82</td>
</tr>
<tr>
<td>Halon 1211 (CF₃CIBr) Bromochlorodifluoromethane</td>
<td>16</td>
<td>7.9</td>
</tr>
</tbody>
</table>
To find the trend of total column ozone before and after the splitting of ozone hole over Antarctica, the yearly averaged value of TCO for both Halley bay and SPO are plotted against years within our period of study. The trend of TCO is assessed through simple linear regression between TCO and years. To validate the results obtained, same trend analysis is done over the stations near Antarctica.

To analyze the result obtained from the trend analysis of TCO, the value of few ozone depleting substances (ODS) over Antarctica: CFC-11, CFC-12, CFC-113, Methyl chloroform, Carbon tetrachloride, Halon-1211 are considered. The ozone depleting potential (ODP) of each of these ODS are mentioned in Table 2. These ODS data are averaged for each year and are also plotted against years. The result is also verified with $^{18}O$/$^{16}O$ ratio in CO$_2$ over Antarctica. These data are also averaged for each year and plotted against years before and after splitting of ozone hole over Antarctica.

3. The total column ozone trend over two Antarctic stations Halley Bay and SPO is showing a decreasing trend during the period taken for study before splitting of ozone hole on 2002 [Figs. 1(a&c) respectively] and an increasing trend after splitting of ozone hole [Figs. 1(b&d) respectively]. To describe the observation TCO value of the nearby stations during the same period of study are analyzed. One of the nearby stations Perth depicts a decreasing trend both before and after splitting of the ozone hole while three other nearby stations Tutuila, Mauna Loa and Wallops Island are showing an increasing trend for both time periods. In the case of Perth the rate of decrease of TCO trend is much more pronounced after the splitting of ozone hole [Figs. 2(a&b)] while in the case of Tutuila [Figs. 2(g&h)], Wallops Island [Figs. 2(e&f)] and Mauna Loa [Figs. 2(c&d)], the rate of increase of TCO trend has been much suppressed after the splitting of ozone hole.

TCO trend analysis over the nearby stations (Perth, Mauna Loa, Wallops Island, Tutuila) indicates that there may be an enhanced transport of ozone from these stations towards Antarctica after the splitting of ozone hole which may cause the increasing trend over the Antarctic stations (Halley Bay & SPO). The enhancement of ozone transport from the nearby stations may be due to higher rate of diffusion of ozone from these stations to the Antarctic stations. Again the sudden stratospheric warming (SSW) phenomenon after the splitting of ozone hole in 2002 reduces the polar vortex activity (Varotsos, 2004) and may enhances the drag of ozone from the nearby stations.

To verify the observations over Antarctic stations, ODS trends are also analyzed which showing that there is a sharp decrease of ODS’s after the splitting of ozone hole.

CFC’s are made up of chlorine, fluorine and carbon atoms. They may decompose as they move from troposphere to stratosphere releasing Cl radical that acts as a catalyst for ozone depletion. The mechanism (Molina and Rowland, 1974) is as follows:

\[
\text{CFCl}_3 \rightarrow \text{CFCl}_2 + \text{Cl} \quad (1)
\]

\[
\text{Or, CF}_2\text{Cl}_2 \rightarrow \text{CF}_2\text{Cl} + \text{Cl} \quad (2)
\]

\[
\text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2 \quad (3)
\]

\[
\text{ClO} + \text{O} \rightarrow \text{Cl} + \text{O}_2 \quad (4)
\]

\[
\text{Net} : \text{O}_3 + \text{O} \rightarrow 2\text{O}_2 \quad (5)
\]

Again, ClO dimer is also involved in ozone depletion (Molina and Molina, 1987)

\[
\text{ClO} + \text{ClO} + \text{M} \rightarrow (\text{ClO})_2 + \text{M} \quad (6)
\]

\[
(\text{ClO})_2 + \text{hv} \rightarrow \text{Cl} + \text{ClOO} \quad (7)
\]

\[
\text{ClOO} + \text{M} \rightarrow \text{Cl} + \text{O}_2 + \text{M} \quad (8)
\]

\[
2(\text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2) \quad (9)
\]

\[
\text{Net} : 2\text{O}_3 \rightarrow 3\text{O}_2 \quad (10)
\]

where, $\text{hv}$ denotes UV-photon and M signifies collisional Chaperone, either N$_2$ or O$_2$ and K is the pressure-temperature dependent rate constant of the rate limiting step.

Halons also release Br radical along with Cl radical which also depletes ozone (McElroy et al., 1986)

\[
\text{ClO} + \text{BrO} \rightarrow \text{Cl} + \text{Br} + \text{O}_2 \quad (11)
\]

\[
\text{ClO} + \text{BrO} \rightarrow \text{Br} + \text{OCIO} \quad (12)
\]

\[
\text{ClO} + \text{BrO} \rightarrow \text{BrCl} + \text{O}_2 \quad (13)
\]

\[
\text{BrCl} + \text{hv} \rightarrow \text{Br} + \text{Cl} \quad (14)
\]

\[
\text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2 \quad (15)
\]

\[
\text{Br} + \text{O}_3 \rightarrow \text{BrO} + \text{O}_2 \quad (16)
\]

\[
\text{Net} : 2\text{O}_3 \rightarrow 3\text{O}_2 \quad (17)
\]
Fig. 3. Trends of ozone depleting substances (ODS) over Antarctica after splitting of ozone hole

Figs. 4(a&b). Trends of O\textsuperscript{18}/O\textsuperscript{16} ratio in CO\textsubscript{2} over Antarctica (a) before splitting of ozone hole and (b) after splitting of ozone hole
All the ozone depleting substances (CFC-11, CFC-12, CFC-113, Methyl chloroform, Carbon tetrachloride, Halon-1211) (Fig. 3) are showing a decreasing trend after splitting. The decrease of ODS over Antarctica supports the observation as the decrease of ODS causes less destruction of ozone over that region. So net amount of ozone over that region increases which causes the increasing trend of TCO over Antarctica after splitting.

The isotopic oxygen (O18/O16) ratio in CO2 acts as a precursor of temperature which has an adverse relationship with temperature. To validate our results over Antarctic stations the trend analysis of this ratio is performed. It is observed that the isotopic oxygen (O18/O16) ratio of CO2 has a decreasing trend before and after splitting of ozone hole [Figs. 4(a&b)] though after the splitting of the ozone hole, the rate of decrease is much pronounced.

The higher decreasing trend of O18/O16 ratio in CO2 over Antarctica after the splitting of ozone hole indicates an increasing rate of temperature over that region. The formation of ozone is an endothermic process, so increase of temperature causes the higher production of ozone (Le-Chatelier’s principle). The decreasing trend of the ratio or the increasing trend of temperature supports the observations of increasing TCO trend over Antarctica after splitting of ozone hole in accordance to the Le-Chatelier’s principle.

4. The use of ODS over Antarctica have been reduced substantially after several treaty for protection of ozone layer like Vienna Convention, Montreal Protocol and being banned by WMO, thus lowering the chance of ozone depletion hence favouring ozone formation. The sudden stratospheric warming after the splitting of ozone hole as mentioned by Varotsos, 2004, reduces the polar vortex activity and drags ozone from the nearby stations like Perth, Mauna Loa, Wallops Island and Tutuila. As a result ozone concentration over Antarctic stations slightly increases after splitting. It agrees fairly well with our observed results and increased of temperature is also verified considering the variations of O18/O16 ratio in CO2 over Antarctica.

References


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**UNUSUAL SNOWFALL AND THUNDERSQUALLS OVER WESTERN HIMALAYAN REGION DURING 2012**

1. A wide variety of weather systems such as monsoon circulations, tropical disturbances, western disturbances (WDs) and easterly waves affect the weather of Indian region. Western Himalayan region (WHR) experiences weather mainly due to WDs in winter season like strong winds, snowfall, rainfall and avalanches. Some weather events are severe in nature, which are associated with mainly active WDs and induced low pressure systems. Thunderstorm activities in pre-monsoon season and wind confluence with westerlies during monsoon season causes severe weather events like cloud bursts and heavy rainfall.

Many studies related to WDs and their impacts on Indian weather were carried out by many researchers. Agnihotri and Singh (1982) studied the WDs approaching northwest India & adjoining areas during winter period (November-March) with the help of satellite cloud imageries. Veeraraghavan and Nath (1989) studied about the temperature distribution of the top of the clouds...