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2 The ozone hole measurements at the Indian station Maitri in Antarctica

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18 **Short title:** Ozone hole at Maitri

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40 HIGHLIGHTS

- 41 • First-time analysis of chemical ozone loss at Maitri station in Antarctica
- 42 • Loss amounts to 170 DU or 40–50%,as for the Antarctic vortex average
- 43 • Largest loss in 2006 and smallest in 2002 in agreement with meteorology
- 44 • Maitri measurements are representative of the Antarctic vortex measurements

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59 **Abstract**

60 Stratospheric ozone is a trace gas of great importance as it filters harmful ultraviolet radiations
61 reaching the earth surface. Since ozone influences temperature and dynamics of the
62 stratosphere, it is also a climate-relevant gas. Significant changes in the stratospheric ozone
63 are, therefore, a great concern for human health and climate. India has a polar research
64 programme and has two research stations in Antarctica; Maitri (70.4° S, 11.4° E, since 1989)
65 and Bharati (69.2° S, 76.2° E). Semi-regular measurements of total column ozone (TCO) are
66 carried out to monitor the changes in the ozone layer there. Here, we use the available TCO
67 measurements from Maitri for the winters of 1999–2003 and 2006, to estimate the chemical
68 ozone loss for the first time at the station. We estimate the largest ozone loss (59% or 180 DU)
69 in 2006, and smallest in 2002 and 1999 (44% or 160 DU) among the winters; consistent with
70 the meteorology, as the winter 2006 was the coldest and 2002 was the warmest with the first-
71 ever sudden stratospheric warming over Antarctica. The Maitri ozone loss analysis is found to
72 be representative for the whole Antarctica as assessed from the comparison with the average
73 TCO from all Antarctic stations and satellite overpass TCO observations. The study, henceforth,
74 demonstrates the value and significance of continuous monitoring of the ozone hole at Maitri
75 to assist the policy decisions such as the Montreal Protocol and its amendments and
76 adjustments.

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78 **Key words:** Antarctic ozone hole; Stratosphere; Climate Change; Maitri; Bharati

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81 1. Introduction

82 Ozone is a highly reactive triatomic molecule and is abundant in the stratosphere at about 10–
83 50 km, with its peak around 25–35 km in the tropical latitudes. The concentration of ozone in
84 the stratosphere (i.e. the ozone layer) protects the earth from harmful ultraviolet (UV)
85 radiations. Due to the increase in chlorofluorocarbons (CFCs) in the atmosphere after
86 industrialisation, stratospheric ozone started to decline in the polar regions by late 1970s
87 (Farman et al., 1985; Bodeker et al., 2005; Müller et al., 2008; WMO, 2018). Measurements
88 from the ground and space have confirmed that the depletion of ozone layer started in the
89 late 1970s and deepened further and reached a point of saturation in the Antarctic in the early
90 1980s (Kuttippurath et al., 2018a). The space-based total column measurements exposed the
91 spatial extent of ozone hole (Stolarski et al., 1986). This situation in Antarctica lead to the
92 seasonal ozone loss and appearance of ozone hole over there (WMO, 2014). Since the
93 stratospheric temperatures are lower, polar vortex is stronger and polar stratospheric clouds
94 (PSCs) are more frequent and widespread, the ozone loss is strong in Antarctica as compared
95 to that of the Arctic (WMO, 2018). The ozone loss is observed to be significant only in the
96 colder Arctic winters such as 1995, 1996, 2000, 2005, 2011 and 2020 (Manney et al., 2011,
97 2020; Rex et al., 2004). In Antarctica, the ozone loss is severe in all winters and show similar
98 loss of about 45–55% or around 175 DU (Kuttippurath et al., 2013; Sonkaew et al., 2013; Tilmes
99 et al., 2006; Huck et al., 2004). There were a few exceptions to this too, such as the winters
100 with significant warming in 1988, 2002 and 2019 (e.g. Kanzawa and Kawaguchi, 1990;
101 Kuttippurath et al., 2015).

102 Significant reduction in ozone has also been observed in the mid-latitudes due to the high
103 levels of halogen compounds in the atmosphere since the 1980s (Steinbrecht et al., 2011; Nair

104 et al., 2013; Tully et al., 2015; WMO, 2018). Studies observe a decrease in ozone of about -
105 0.7%/yr in the mid-latitudes and 4–5% in the subtropics prior to 1997 during which the
106 halogens peaked in the mid-latitudes (Nair et al., 2015; Krzyścin, 2012; Steinbrecht et al., 2006;
107 WMO, 2018). However, recovery of ozone is found afterwards, about -0.2 ± 0.08 to
108 $-1\pm 0.07\%$ /yr in the mid-latitudes and -0.2 ± 0.06 to $-0.7\pm 0.05\%$ /yr in the subtropics in the
109 upper stratosphere (e.g. Nair et al., 2015). Similar estimates were also found in other long-
110 term ozone trend studies for the mid-latitudes (e.g. Weber et al., 2018; WMO, 2018). The
111 increase in ozone is attributed to the dynamics related to the quasi-biennial oscillation, El
112 Niño–Southern Oscillation. Therefore, the mid-latitude and low latitude ozone change will be
113 decided by the dynamics and the amount of stratospheric chlorine in the regions (e.g. Randell
114 et al., 2002). On the other hand, the ozone changes in the high latitudes were attributed to the
115 reduction in halogen loading in the atmosphere (e.g. WMO, 2018). Also, there is a clear
116 reduction in frequency for the occurrence of ozone loss saturation over the period 2001–2017
117 in the Antarctic, which underlines the impact of phasing out of ozone-depleting substances
118 (ODSs) through Montreal protocol (Kuttippurath et al., 2018a). Although statistically significant
119 positive trends are observed in the Antarctic (e.g. Chipperfield et al., 2017; Kuttippurath and
120 Nair, 2017; Solomon et al., 2016; Salby et al., 2015), no clear trends are found in the Arctic
121 ozone due to large dynamical variability there.

122 India has three research bases in Antarctica: the first station was established in 1980 as
123 Dakshin Gangotri (70.4° S, 11.4° E), Maitri (70.4° S, 11.4° E) in 1989 and Bharati (69.2° S, 76.2°
124 E) in 2012, and the latter two are only currently active. The Ministry of Earth Science (MoES)
125 of India and its operational and research agencies make different types of observation at the
126 stations. The station Maitri is located in the rocky coasts of Queen Maud Land at the edge of
127 the Antarctic continent, which is devoid of snow throughout the year and experiences wind

128 from both ocean and inland (Ganguly, 2012). There are semi-regular total column ozone (TCO)
129 measurements at Maitri since the early 1990s using Brewer Spectrophotometer. There are
130 studies using ozone measurements from Maitri, but mostly discussed the seasonal and
131 interannual changes in ozone, and their relationship with meteorology such as temperature,
132 pressure and winds (e.g. Ali et al., 2017; Ganguly and Joel, 2010; Ghude et al., 2005; Lal and
133 Ram, 2013). In a long-term study using ground-based and satellite datasets for the period
134 1979–2001, the seasonal variation in TCO over Maitri was found to be more pronounced than
135 other temporal variability. The study also found a declining trend in the monthly average TOC
136 during the period 1979–1988 and was attributed to the increased CFCs in the stratosphere
137 (Ganguly and Joel, 2010). In another study, TOC measured at Maitri showed good agreement
138 with stratospheric temperature anomaly (Ghude et al., 2006, 2005). Although, there are
139 studies using Maitri ozone measurements, the chemical ozone loss was never estimated with
140 these measurements. The primary goal of the ozone measurements in Antarctica is ozone loss
141 estimation and monitoring the temporal changes of ozone hole. Therefore, we estimate the
142 chemical ozone loss analyses using the available measurements (6 years) of Maitri TCO
143 measurements.

144 2. Methods

145 2.1 Ground-based and satellite measurements

146 Since we estimate ozone loss at Maitri, we use the ground-based measurements from the
147 station in the Antarctic. Measurements from other Antarctic stations are also considered to
148 compare with that of Maitri (e.g. Kuttippurath et al., 2013). The co-coordinates of the stations
149 including Maitri are shown in **Figure 1**. The figure also shows the potential vorticity (PV) maps
150 on 22 September 2002 as the vortex was very much disturbed with a major warming and on

151 24 September 2006, when the Antarctic experienced the biggest ozone hole ever in the
152 observed history. In both occasions, the Maitri station was inside the polar vortex, suggesting
153 that the station is pretty much inside the vortex in most dynamical conditions. However, please
154 note that the vortex position will be different at different altitudes. We use the measurements
155 made by the Brewer Spectrometer (MkIV, 153) at Maitri. Brewer instruments employ
156 differential absorption of ozone in the UV region for ozone measurements (Brewer et al.,
157 1973). Individual observations are made by looking at the direct sun on a clear sky and are
158 averaged to a daily mean and the measurements are limited to SZA (solar zenith angle) $<80^\circ$.
159 The measurements are better than that of the Dobson measurements and accuracy of the
160 instruments are about 0.5% of TCO or 1 DU (Scarnato et al., 2010; Kuttippurath et al., 2018b).
161 A comprehensive study on polar ozone measurements by different instruments with a detailed
162 analysis on their strength and limitations are presented in Kuttippurath et al. (2018b).

163 We have used the winter measurements in Antarctica, which are considered from May through
164 November. On the other hand, most Maitri measurements are performed during winter and
165 spring months as compared to other stations in the Antarctic. The measurements are available
166 for the years 1999–2006. However, the measurements in 2004 and 2005 were during the
167 summer, which are not considered as we estimate the ozone loss in winter and spring. There
168 are 40–64 days of measurements in each year and are mostly during the period September–
169 November, because the observations were primarily aimed at monitoring the changes in
170 Antarctic ozone hole. Additionally, the Brewer measurements are limited to the availability of
171 sunlight and depend on SZA, which is why most measurements are done in spring.

172 The ground-based measurements at Maitri are compared to the TOMS (Total Ozone Mapping
173 Spectrometer) and OMI (Ozone Monitoring Instrument) measurements of the respective

174 years. The TOMS retrievals make use of two wavelengths: 331.2 and 360 nm, but 270–500 nm
175 for OMI. The measurements during the period 1999–2003 are compared to the version 8.5
176 TCO from TOMS on-board Earth Probe (Wellemeyer et al., 2002). The 2006 measurements are
177 however, compared to the OMI measurements as the TOMS instrument was not operational
178 from 2005 onwards (e.g. McPeters et al., 2015). The uncertainty of satellite measurements
179 (both TOMS and OMI) is about ± 1 –3% or the mean bias is about ± 4 DU, which depends on the
180 station and satellite instrument for for $SZA < 84^\circ$ (Kuttippurath et al., 2018b; Kroon et al., 2008;
181 Balis et al., 2007; Levelt et al., 2006).

182 **2.2 Ozone loss calculation**

183 We apply the passive method (Goutail et al., 2005; Kuttippurath et al., 2010) to estimate ozone
184 loss from TCO measurements at Maitri and other stations. However, note that there are
185 different methods for estimating the ozone loss, as discussed in Harris et al. (2002). The
186 method uses a passive tracer simulated by a chemical transport model (CTM) and we use the
187 REPROBUS model simulations for the passive tracer simulations (Lefèvre et al., 1998). It is a
188 three-dimensional CTM with a comprehensive description of stratospheric chemistry. The
189 model runs were forced by the European Centre for Medium-Range Weather Forecasts
190 (ECMWF) operational analyses, with 60 vertical levels from 1000 to 0.1 hPa. The model uses
191 the hybrid sigma-pressure vertical coordinate and vertical advection is computed directly from
192 the wind fields. Chemical species are transported by a semi-Lagrangian method (Williamson
193 and Rasch, 1989). Note that we have considered only the passive tracer simulations from the
194 model results. The tracer is initialised on first of July so that the ozone loss on that day would
195 be zero. The chemical ozone loss is then estimated by subtracting the passive tracer from TCO
196 measured by the ground-based instrument at respective stations.

197 Large changes in ozone in the polar regions are very much related to the circumpolar
198 circulation, position of polar vortex, and the special meteorology related to the vortex in winter
199 and spring there (e.g. Hood and Soukharev, 2005; Huck et al., 2004; Solomon, 1999). The polar
200 vortex acts as a containment vessel and is effectively separated from the mid-latitude air. Very
201 low temperatures inside the vortex and high winds at the edge of the vortex are the key feature
202 of this dynamical system. This situation facilitates the formation of PSCs and the high winds at
203 the vortex edge prevent mixing of air masses from the adjacent middle latitude regions (e.g.,
204 Drdla and Müller, 2012). This makes a unique heterogeneous chemistry inside the vortex and
205 set conditions for chlorine activation and ozone loss. Therefore, the ozone loss has to be
206 estimated within the vortex. We have used the ECMWF meteorological files (Dee et al., 2011)
207 to compute the potential vorticity (PV) and then to estimate the edge of the vortex using the
208 method defined by Nash et al. (1996) to segregate the vortex measurements. To avoid the PV
209 filaments in vortex edge calculation, we have also used additional criteria of 35 PV units (pvu,
210 and one pvu is $10^{-6} \text{ Km}^2 \text{ kg}^{-1} \text{ s}^{-1}$) and 63° Equivalent Latitude (EqL, Müller et al., 2005). That is,
211 the measurements are considered to be inside the vortex, when they satisfy the conditions of
212 Nash et al. (1996) vortex edge criterion, > 35 pvu and $> 63^\circ$ S EqL conditions.

213 3. Results and Discussion

214 3.1 Meteorology of the winters

215 The Maitri station is located at 70° S, which is almost inside the polar vortex in most winters.
216 **Figure 2** shows the average polar cap temperature in the Antarctic for different winters at 70
217 and 100 hPa. The temperature at 70 hPa (in the lower stratosphere) show about 195 K from
218 July to mid-September in all winters, which gradually increases until the end of November. The
219 temperatures from mid-September to November normally decide the ozone loss chemistry in

220 the lower stratosphere and final warming of Antarctic winters. The temperatures below 195 K
221 facilitate the formation of polar stratospheric clouds (PSCs) on which the halogens would be
222 activated and make ozone loss when the vortex would be exposed to sunlight in spring. The
223 evolution of lower stratospheric temperature is different in each winter (Kuttippurath et al.,
224 2013; Tilmes et al., 2006; Huck et al., 2005). For instance, the temperature increases from 195
225 K in mid-September to 206–212 K by the end of November in 1999, 2001, 2003, and 2006.
226 However, PSCs can still be present and thus, chlorine activation can drive ozone loss during the
227 period (Grooß et al., 2011; Müller et al., 2018). There were minor warmings in early September
228 2000 and mid-September in 2006, about 2–5 K. Conversely, the winter 2002 was dynamically
229 disturbed from July onwards with minor warmings and then this particular dynamical situation
230 finally lead to a major warming with a vortex split event on 25 September 2002 (e.g. Hoppel et
231 al., 2003). This was the first-ever vortex split major warming event recorded in the
232 measurement era. The temperature increased from 198 to 217 K from mid- to the end of
233 September in that winter. Therefore, the warmest was 2002 and the coldest was 2006 among
234 the analysed winters. The evolution of temperature is similar at 100 hPa, but about 3 K higher
235 until mid-September and about 1–5 K smaller afterwards, depending on the winter. These
236 dynamical conditions are also reflected in the TCO measured from satellites (TOMS–OMI) as
237 illustrated in **Figure 2**.

238 The winters show minor warmings in mid-September and consequently resulted in distortion
239 or elongation of the polar vortex in 2000, 2001, 2003 and 2006. However, a very quiet and
240 calm September was evident in 1999 and therefore, an undisturbed, concentric and circular
241 polar vortex is evident in that winter. In 2002, the first-ever vortex split event occurred in the
242 southern polar region and is clearly captured by TCO map, as shown in Figure 2. Apart from
243 that, we also wanted to show the position of Maitri station in different types of vortex

244 disturbances. The maps depict that the station is always inside the vortex even during the
245 vortex split event. This would make the station ideal for ozone loss and ozone trend studies in
246 the southern polar region. We have also marked the Indian station Bharti in the maps to
247 compare the position of both stations in terms of their vortex representation. It exhibits that
248 Bharti station resides at the vortex edge on most occasions when the vortex is slightly
249 disturbed. Note that we have shown the TCO with ozone hole 220 DU contour, not the vortex
250 edge to demonstrate the position of polar vortex in the maps.

251 3.2 Temporal evolution of ozone

252 **Figure 3** shows the ozone measurements at Maitri compared to the TOMS–OMI and the
253 average of all ground-based station measurements (without Maitri) in Antarctica. In general,
254 the Maitri measurements are made in September, October and November months. Therefore,
255 the measurements show below 220 DU in September and early October. The measurements
256 in November or even mid-October onwards show large interannual variability. This is an
257 expected result as the minimum ozone in Antarctica usually occurs during the period (Huck et
258 al.,2005; Müller et al., 2008; Grooß et al., 2011; Kuttippurath et al., 2013). Ozone increases
259 gradually afterwards due to mixing with the mid-latitude air. Therefore, the ozone shows a
260 steep decline in September, from about 250–200 DU to 150–110 DU, depending on winters.
261 The smallest ozone measurements in the winter are found in October, about around 100–120
262 DU in the coldest winters of 1999, 2003 and 2006. However, the ozone values show a slight
263 increase (10–20 DU) from mid-October onwards such as in 2000. The November
264 measurements exhibit ozone values between 150 and 300 DU in different winters. The
265 situation in warm winters is slightly different as shown by the ozone distribution in 2002. As
266 demonstrated by temperature, the winter was highly disturbed with minor warmings from July

267 through September and then ended up with a major warming in late September with a vortex
268 split. Therefore, excursion of vortex to mid-latitudes, and distortion, elongation and split of the
269 vortex would cause such large and episodic changes in ozone distribution. There was an
270 unusual chlorine deactivation, which is also one of the reasons of the high ozone values in 2002
271 (Grooß et al., 2005). The intermittent high values of ozone throughout the winter months show
272 the intense dynamical activity in the winter. Also, the high ozone values associated with the
273 minor warmings in other winters (e.g. late September in 1999 and mid-September in 2006)
274 and final warming (e.g. end of November in 2001, 2002 and 2003) are clearly captured by the
275 Maitri measurements. A similar distribution of ozone can be also found in the measurements
276 at the Sejong station (62° S, 58° W) in the western Antarctica (Koo et al., 2018). Note that the
277 total ozone changes inside the vortex are largely decided by diabatic descent inside the vortex,
278 the adiabatic motions related to planetary wave activity, and convergence or divergence
279 related to the changes of tropospheric height. Therefore, the variations of ozone values are
280 expected in daily measurements due to the dynamics.

281 **Figure 3** also shows the comparison between Maitri measurements and TOMS-OMI overpass
282 ozone measurements at Maitri. In addition, the Maitri measurements are also compared to
283 the average of all other ground-based station measurements in Antarctica. The details of other
284 station measurements are given in Figure 1 and Table 1 of Kutippurath et al. (2013). However,
285 please note that we have exempted Dumont d'Urville and Concordia measurements from the
286 averaged data. Therefore, the other seven station measurements are used for the station
287 average. The averaged data show the complete evolution of ozone in the winter, as the Maitri
288 data start only in September. The comparison with station-averaged data with Maitri data
289 would allow us to assess the spatial variability of TOC in Antarctica and representativeness of
290 the individual station measurements (e.g. Maitri) for the entire region. On top of these, the

291 use of multiple data displays the synergetic use of various types of observations for better
292 interpretation of analysed results.

293 The TOMS-OMI measurements start by mid-August over the Antarctica and the overpass at
294 Maitri shows good agreement with the ground-based observations throughout the winters.
295 The differences are mostly within 5%, which is also the uncertainty of the satellite overpass
296 measurements (McPeters et al., 2008; Kroon et al., 2008; Kuttippurath et al., 2018b).
297 Nevertheless, the difference between the Brewer and satellite measurements at Maitri is
298 slightly larger during warming periods as shown by the measurements in November 2003 and
299 2006. Previous analyses have also found similar results when ground-based measurements are
300 compared to the satellite measurements. For example, Balis et al. (2007) found an
301 overestimation (about 2%) of TOMS measurement with ground-based measurements in the
302 southern hemisphere. Similar results were also found when satellite measurements were
303 compared to that of ground-based measurements in the southern latitudes for the period
304 1996–2000, where the estimation was about 3.3% (Bramstedt et al., 2003). An analogous result
305 was observed when Zhongshan measurements were compared to EP-TOMS measurements for
306 which the satellite measurements were 2.55% higher than that of ground-based
307 measurements. The OMI measurements were also found to be overestimated (2–7%) the
308 ground-based measurements at Marambio and Belgrano (Balis et al., 2007; Kuttippurath et al.,
309 2018b). The satellite overpass measurements are the area-averaged value of about 100 km,
310 which would be slightly different from the point-measurements made by the Brewer or
311 ground-based instrument at the station. In addition, when the temperature increases in spring,
312 the ozone loss stops and ozone hole reduces its size by November. This vortex erosion would
313 be another reason of the differences between ground-based and space-based observations in
314 spring and during warm winters.

315 On the other hand, the all station averaged data show the complete seasonal evolution of TOC
316 in Antarctica. The ozone starts to decrease in early July, the reduction in ozone gradually
317 progresses in August and the rate of decrease peaks in September. The lowest ozone values
318 are observed during the end of September and early October, and the ozone picks up due to
319 mixing with mid-latitude air afterwards until the end of November, as also found in the Maitri
320 ground-based measurements. The station average and Maitri data show very good agreement
321 up to the minimum ozone period (early October). The average data show slightly higher values
322 as these data include measurements from the edge stations such as Marambio, Rothera and
323 San Martin, where the ozone values are relatively higher than other stations (e.g. Kuttippurath
324 et al., 2013; Zhang et al., 2017). As stated previously, the planetary wave activity can disturb
325 the polar vortex at times, which would make some stations outside the vortex (e.g. Marambio
326 and Rothera) and thus show slight differences in ozone measurements between satellite and
327 ground-based measurements during warming periods and at the end of spring, as found in the
328 figure.

329 **3.3 Chemical ozone loss in the winters 1999–2003 and 2006**

330 We have analysed the ozone loss in 6 winters; 1999–2003 and 2006, and have averaged the
331 ozone loss values for 7 days to suppress the daily variations in ozone to make a more robust
332 ozone loss estimate. In 1999, the winter was not very cold as compared to other winters. The
333 measurements are mostly restricted to October and November, and there is a constant ozone
334 loss of about 150 DU during the period. In 2000, the ozone loss was 60 DU in August and it
335 increased to 130 DU in early September and peaked to 160 DU by end of September. The ozone
336 loss in 2001 was very severe and the loss was about 60 DU in mid-August, 80 DU in early
337 September and the loss peaked by early October to 160 DU. The ozone loss in the warm winter

338 also show a similar loss of about 170 DU in October. The ozone loss evolution shows similar
339 features and loss values in 2003 and 2006, about 80 DU in September to 150–160 DU in
340 October. The loss in peak period in October was relatively higher in 2006 and 2003, about 170
341 DU. The maximum ozone loss is generally found in early October as the PSCs terminates with
342 relatively higher temperatures during the period.

343 We have also estimated the peak ozone loss in relative units for the period 15 September – 15
344 October (ozone loss/passive tracer multiplied by 100). The maximum loss estimated in 1999 is
345 about 43% in 1999, 57% in 2000, 56% in 2001, 46% in 2002, 57% in 2003 and 59% in 2006. The
346 ozone loss in 2002 was slightly different from other winters, as the winter was warmer than all
347 other winters. The year witnessed the first major warming with a vortex split event in the
348 observational record, which occurred on 25 September 2002. The ozone loss shows a sharp
349 decline afterwards (e.g. Feng et al., 2005; Kuttippurath et al., 2013). Therefore, the ozone loss
350 was similar to that of other winters and the peak ozone loss in DU observed by mid-September
351 was lower (10–20 DU) than that of other winters, about 46%.

352 The ozone loss estimated at Maitri compares very well with TOMS-OMI satellite measurements
353 (mostly within 2 DU) in all winters, as also shown in Kuttippurath et al. (2010, 2013). It is
354 interesting to note that the ozone loss estimated at Maitri is very similar to that of the all
355 station average of other ground-based measurements in Antarctica. The differences are mostly
356 about 1–2 DU throughout the winter, except for one or two measurements in some winters
357 such as the loss estimated at Maitri for November 2003. This suggests that the Maitri
358 measurements are representative of the entire Antarctic vortex and the measurements are
359 highly valuable for monitoring the temporal changes in the Antarctic ozone hole. The ozone
360 loss estimated for the winters show comparable values to that estimated by previous studies.

361 For instance, our results are comparable to the values estimated by Huck et al. (2007) and are
362 about $105\text{--}120\pm 10$ DU for the winters discussed. The ozone loss at Maitri for the winters 1999
363 and 2000 are also comparable to that found from the POAM satellite measurements (Hoppel
364 et al., 2003) and SLIMCAT model simulations (Feng et al., 2005), as they also estimate similar
365 ozone loss values. Our analyses are in good agreement with the partial column loss estimated
366 ($130\text{--}145\pm 10$) by Tilmes et al. (2006) for 1996 and 2003. The Maitri results are in very good
367 agreement with that of Kuttippurath et al. (2013) as they also estimate a loss of about 150--
368 170 ± 10 DU for the winters 1999–2003 and 2006. However, our results for 2000–2001 are also
369 comparable to the total column ozone loss estimated by Sinnhuber et al. (2002) and the partial
370 column ozone loss found in Strahan and Douglas (2018).

371 **4. Conclusions**

372 India has a well-planned polar research programme and has ozone measurements since 1990s
373 in Antarctica. We have considered TCO measurements from the Maitri station of Antarctica.
374 The winter TCO measurements by the Brewer instrument are used for the winters 1999–2003
375 and 2006. The winters 2000, 2001, 2003 and 2006 were colder winters of Antarctica, and 2006
376 was coldest among them, in which the largest ozone hole was observed. Therefore, ozone loss
377 amounted to 170 DU or 57–59% in 2006. The winters 1999 and 2002 were relatively warm and
378 thus ozone loss was restricted, about 43–46%, and the winter 2002 experienced the first vortex
379 split event in the southern polar region in the observational era. This dynamical situation led
380 to the smallest ozone hole with lower ozone loss (43% in September) in that winter. The
381 observed ozone loss matches very well with the all station average that includes
382 measurements from nine stations in the Antarctic continent; implying that the Maitri
383 measurements very much represent the ozone loss of the entire Antarctic region. This suggest

384 that the station is inside the polar vortex in most winters. However, the differences in spring
385 measurements and during warming periods indicate that the erosion of polar vortex. The
386 analyses presented suggest the continued monitoring of ozone in the region to monitor one of
387 the important trace gases on the earth that influences public health and changes in climate.

388

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398 **Data availability**

399 The data used in this study are publicly available (<https://woudc.org/>). The analyses codes can
400 be provided on request. The OMI data are available on [https://earthdata.nasa.gov/earth-
401 observation-data/near-real-time/download-nrt-data/omi-nrt](https://earthdata.nasa.gov/earth-observation-data/near-real-time/download-nrt-data/omi-nrt). Since the satellite data used are
402 already freely available on public domains, the analysed data can also be provided for any
403 scientific study.

404 **Code availability**

405 The analyses codes are available on request.

406 **Competing Interests**

407 The authors confirm that there are no known conflicts of interest and no competing interests.

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597 **FIGURE CAPTIONS**

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599 **Fig. 1: The ozone measurement stations in Antarctica.** The Maitri station together with other
600 ozone observing stations in Antarctica. The stations are represented by their first three letters
601 (e.g. MAR – Marambio, MCM – Arrival Heights/McMudro, MIR – Mirny, DAV – Davis, SYO –
602 Syowa, MAI – Maitri, NEU – Neumayer and SPL – South Pole). The potential vorticity maps for
603 24 September 2002 and 24 September 2006 are also shown.

604 **Fig. 2: Temporal evolution of wintertime polar meteorology.** Evolution of polar cap (60° – 90° S)
605 temperatures at 100 and 70 hPa in Antarctica. The total column ozone (TCO) measurements
606 from satellite measurements (TOMS–OMI) on 25 September and October mean for each year
607 are also shown. The vortex split event occurred in the Antarctic was on 25 September 2002
608 and is selected to represent the dynamics of polar vortex. The ozone hole criterion of 220 DU
609 is also demarcated on the ozone maps. The horizontal dotted lines in temperature graphs (left
610 represent 195 K (i.e. Polar Stratospheric Cloud threshold).

611 **Fig. 3: Ozone measurements at Maitri and other Antarctic stations.** The ozone measurements
612 at Maitri in Antarctica for the period 1999–2003 and 2006. The measurements averaged for all
613 other stations in Antarctica and TOMS–OMI satellite overpass at Maitri are also shown. The
614 dotted horizontal line represents the ozone hole criterion 220 DU, and 100, 200 and 300 DU.

615 **Fig. 4: Ozone loss at Maitri and the Antarctic ozone hole.** The chemical ozone loss estimated
616 with the Maitri measurements in Antarctica together with that of the mean-ozone computed
617 from the measurements of other Antarctic stations for the period 1999–2003 and 2006. The
618 ozone loss estimated with the TOMS–OMI satellite overpass observations at Maitri are also
619 shown. The dotted horizontal line represents the ozone loss of 50, 100, 150, 200 and 250 DU.







