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**Article:**

Kuttippurath, J, Ardra, D, Raj, S et al. (1 more author) (2023) A seasonal OH minimum region over the Indian Ocean? *Atmospheric Environment*, 295. 119536. ISSN 1352-2310

<https://doi.org/10.1016/j.atmosenv.2022.119536>

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1 **A seasonal OH minimum region over the Indian Ocean?**

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48 **HIGHLIGHTS**

49 There exists a seasonal OH minimum region over Indian Ocean in spring

50 A secondary minimum in autumn, but values are slightly higher than that in spring

51 SO<sub>2</sub>, CO, O<sub>3</sub> and H<sub>2</sub>O chemistry play a key role in the observed minimum in the region

52 The OH minimum can affect the air quality in the Indian Ocean region

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72 **ABSTRACT**

73 As the hydroxyl radical (OH) is the cleansing agent of the atmosphere, reduction in its concentration is a  
74 great concern for air quality and transport of trace gases across the latitudes and altitudes. In addition, OH  
75 determines the lifetime of most trace gases and non-CO<sub>2</sub> greenhouse gases in the atmosphere. Since many  
76 pollutants have adverse health effects and are greenhouse gases, the changes in OH concentrations directly  
77 or indirectly affect public health and climate. Our analysis with OH data (from Tropospheric Emission  
78 Spectrometer and Copernicus Atmosphere Monitoring Service reanalyses) for the past 14 (2005–2018)  
79 years finds an OH minimum region over Indian Ocean, in the eastern Bay of Bengal at 6°–14°N and 92°–  
80 95°E. The Indian Ocean OH minimum reaches to  $15 \times 10^4$  molec.cm<sup>-3</sup> in April, and a secondary minimum of  
81  $18 \times 10^4$  molec.cm<sup>-3</sup> in September–November. This seasonal minimum found around the Andaman and  
82 Nicobar Islands also hosts an active volcano, which releases noticeable amount of SO<sub>2</sub> (OH sink) throughout  
83 the year. In addition, the biomass burning in spring and thus, the distribution of CO has a profound influence  
84 on the OH distribution in this region as Southeast Asia is one of the global hotspots of biomass burning, and  
85 the Indian Ocean OH minimum is located near that region. The El Niño and La Niño events also control the  
86 tropospheric ozone and CO distribution, and thus the interannual variability of OH minimum there. The  
87 WACCM model simulations reproduce the general latitudinal distribution and average seasonal cycle of  
88 OH, but not the extreme minimum OH values, although the simulations show the annual minimum in winter  
89 (December–January) in both ocean regions, which demands dedicated studies using chemical transport  
90 models. Therefore, this study reveals a seasonal OH minimum over Indian Ocean, which is very likely to  
91 influence the regional air quality and trace gas transport in the tropics.

92

93 **Short title:** Indian Ocean OH minimum

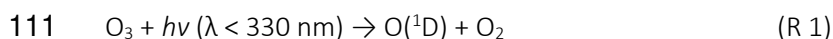
94 **Key words:** Indian Ocean; Stratosphere; troposphere; Pollution; western Pacific Ocean; OH

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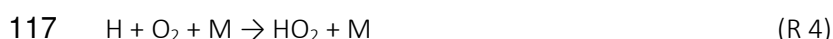
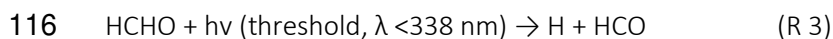
96 **1. Introduction**

97 Hydroxyl (OH) is a short-lived (less than a second) free radical and the most effective scavenger in the  
98 troposphere. It is the major oxidant in the lower troposphere that determines the lifetime of most trace  
99 gases and greenhouse gases (GHGs) such as methane (CH<sub>4</sub>) in the atmosphere (Lelieveld et al., 2016; Nicely  
100 et al., 2018), and therefore, is a climate relevant gas. OH radical is called the “detergent of atmosphere”  
101 due to its role and ability to clean the atmosphere. The general composition of stratosphere is influenced  
102 by the species that are transported from the troposphere. Hydroxyl radicals in the troposphere react with  
103 some short-lived species and convert them into soluble products. Therefore, OH radicals in the troposphere  
104 mask the stratosphere from many tropospheric emissions (Rex et al., 2014). The variability of OH in the  
105 troposphere is key not just for the supply of chemical species such as SO<sub>2</sub> and CH<sub>4</sub> to the stratosphere, but  
106 also for the atmospheric lifetime of several trace gases (Manning et al., 2005).

107  
108 There are multitude of sources and sinks for the hydroxyl radical. The primary production of OH is by the  
109 photodissociation of ozone by ultraviolet (UV) sunlight with a wavelength of the photon (hν) shorter than  
110 330 nm in the presence of water vapor (Levy, 1971):



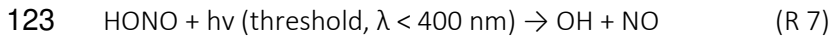
113 Recently, it is found that this source has a relatively small contribution compared to other sources under  
114 polluted conditions (e.g. Elshorbany et al., 2010; Vogel et al., 2003). Photolysis of HCHO is a daytime source  
115 of HO<sub>2</sub> radicals:



119 The conversion of HO<sub>2</sub> to OH depends on the availability of NO.



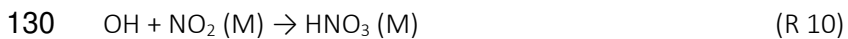
121 The OH radical is also formed by the ozonolysis of alkenes. In addition, nitrous acid (HONO) contributes to  
122 the formation of OH radical:



124 This is a major source of daytime OH concentration (Elshorbany et al., 2010). The OH radical reacts with  
125 reduced and partly oxidised gases such as  $\text{CH}_4$ , CO and non-methane Volatile Organic Compounds  
126 (NMVOC). CO and  $\text{CH}_4$  are the direct sinks of atmospheric OH (Lu et al., 1993).



129 Also, under high  $\text{NO}_x$  conditions, permanent loss processes are dominated by the reaction of OH with  $\text{NO}_2$ .



131 Therefore, the regional variability of OH depends on several factors.

132

133 An OH minimum has been found in the tropical western Pacific centered at  $17^\circ \text{ N} / 158^\circ \text{ E}$ . This “OH hole”  
134 was reported based on the observations of very small values of tropospheric  $\text{O}_3$  in this region (Rex et al.,  
135 2014). The explanation for this is that suppression of primary OH production due to low  $\text{O}_3$  or deficiency of  
136 secondary production due to low NO (Wolfe et al., 2019a,b). It implies that the region has very low  
137 atmospheric pollution or pristine air. Here, we examine whether there is any OH minimum zone over other  
138 ocean basins, e.g. Indian Ocean. Our analyses expose an OH minimum (at the surface level) over Indian  
139 Ocean at around  $12^\circ \text{ N} / 93^\circ \text{ E}$ . Therefore, we present a detailed assessment of the spatio-temporal  
140 variability of this OH minimum for the past 14 years (2005–2018) using the TES (Tropospheric Emission  
141 Spectrometer) reanalysis data. Since the analysis and identification of a minimum value is very sensitive  
142 and could be also data specific, we have used another reanalysis data, the Copernicus Atmosphere  
143 Monitoring Service (CAMS). Furthermore, we have also used a global chemical transport model (CTM) for

144 the simulation of OH in both oceanic regions for examining the representation of OH minimum in the state-  
145 of-the-art CTMs. The distribution of OH is compared to that of CO, CH<sub>4</sub>, HCHO, SO<sub>2</sub>, H<sub>2</sub>O, NO<sub>x</sub>, HNO<sub>3</sub> and O<sub>3</sub>  
146 in the minimum region. Note that there are no measurements available in this region, and therefore, we  
147 have used the reanalysed data and model simulations. The influence of meteorological and oceanic factors  
148 such as clouds, water vapour, precipitation, winds and sea surface temperature (SST) on the variability of  
149 OH is also discussed. The OH minimum over this region is compared to that in the tropical western Pacific  
150 and reasons for these minima are assessed.

151

## 152 2. Data and Methods

153 The TES chemical reanalysis data have a horizontal resolution of 1.1°×1.1° (e.g. Cady-Pereira et al., 2017;  
154 Miyazaki and Bowman, 2017). Chemical reanalysis is a technique in which measurements from multiple  
155 satellites are combined to get a continuous data of atmospheric composition. These data are made by  
156 assimilating the measurements from OMI (Ozone Monitoring Instrument), MLS (Microwave Limb Sounder,  
157 Livesey et al., 2020), TES (Miyazaki and Bowman, 2017) and MOPITT (Measurements of Pollution in the  
158 Troposphere, Deeter et al., 2003) satellite measurements. The reanalysis is made using a global CTM, and  
159 an ensemble Kalman filter that optimises the concentrations of different species (Miyazaki et al., 2015). We  
160 have used O<sub>3</sub>, CH<sub>4</sub>, NO<sub>x</sub>, HCHO, SO<sub>2</sub>, CO, HNO<sub>3</sub> and OH data from the TES reanalysis.

161

162 CAMS is the global atmospheric composition reanalysis made by the European Centre for Medium-Range  
163 Weather Forecasting (ECMWF). It provides 3-dimensional time-consistent quantifications of  
164 meteorological variables and concentrations of aerosols, dust and other trace gases such as OH from 2003  
165 onwards. The reanalysis product offers a gridded data with a spatial resolution of 0.75°×0.75°. It has  
166 relatively smaller biases with respect to the measurements, and is more reliable than that of Monitoring  
167 Atmospheric Composition and Climate (MACC), the previous version of CAMS (Inness et al., 2013). All



168 variables in the CAMS reanalysis are assimilated using the IFS Cycle 42r1 4D-Var. Here, we use the monthly  
169 mean OH data at the surface for the Indian and Pacific Oceans. Further information about the data is  
170 provided in Inness et al. (2019).

171  
172 To analyse the impact of meteorological factors on OH distribution, we have used the Tropical Rainfall  
173 Measuring Mission (TRMM) daily rainfall data with a resolution of  $0.25^{\circ} \times 0.25^{\circ}$  (TRMM, 2011; Kuttippurath  
174 et al., 2021). This dataset contains the output of TRMM Algorithm 3B42 to produce the merged TRMM  
175 precipitation measurements. The NOAA (National Oceanic Atmospheric Administration) Extended  
176 Reconstructed Sea Surface Temperature (ERSST) Version 4 data are also considered (e.g. Huang et al., 2017;  
177 Anandh et al., 2018). These monthly mean data have a spatial coverage of  $2^{\circ} \times 2^{\circ}$ . The National Centers for  
178 Environmental Prediction (NCEP) reanalysis monthly data are considered for wind, which have 17 pressure  
179 levels on a horizontal resolution of  $2.5^{\circ} \times 2.5^{\circ}$ .

180  
181 The NASA-EOS Terra and Aqua spacecrafts are equipped with the MODIS sensor. Terra crosses the equator  
182 southward around 10:30 local solar time (LST), while Aqua crosses northward around 13:30 LST. MODIS  
183 observes the Earth in 36 channels in a spectral resolution from 0.41 to 14  $\mu\text{m}$ . MODIS uses infrared bands  
184 to measure cloud properties in relation to cloud top temperature and pressure. It employs visible and near  
185 infrared channels to derive optical and microphysical cloud parameters (King et al., 2003). We use the  
186 MODIS level 3 gridded monthly mean cloud fraction data with a spatial resolution of  $1^{\circ} \times 1^{\circ}$  over the Indian  
187 Ocean region for the year 2005. The monthly mean data are taken to estimate the seasonal distribution of  
188 cloud fraction. We also use the MODIS monthly active fire product at 1 km spatial resolution. The MODIS  
189 Adaptive Processing System (MODAPS) real-time active fire data are also available through Fire Information  
190 for Resource Management (FIRM). These data are processed by MODAPS to the collection 5 Active fire

191 product using an enhanced contextual fire detection algorithm (Giglio et al., 2003). Here, we examine the  
192 monthly mean active fire data from 2005 to 2018 in the Southeast Asian region adjacent to Indian Ocean.

193  
194 In addition, we have also used the WACCM model simulations to examine the OH minimum over both  
195 oceanic basins. This is a three-dimensional offline CTM with full tropospheric chemistry. The model is driven  
196 by meteorological data from ECMWF reanalysis (Dee et al., 2011). The model has a horizontal resolution of  
197  $1^\circ \times 1.25^\circ$ , and the vertical co-ordinates range from the surface to  $5 \times 10^{-6}$  hPa. The model results are provided  
198 for every 6 h. Further details about the model can be found in Wu et al. (2021) and Marsh et al. (2013).

199  
200 For studying the monthly variations in the distribution of OH and other trace gases, their average for each  
201 month from 2005 to 2018 is estimated. Seasonal averages are computed by finding the mean over the  
202 months DJF (December, January and February) for winter, MAM (March, April and May) for spring, JJA  
203 (June, July and August) for summer and SON (September, October and November) for autumn.

204

### 205 **3. Results and discussion**

#### 206 ***3.1 The OH minimum in Indian Ocean***

207 Fig. 1 (top) shows the global surface OH distribution, and Fig. 1 (bottom) zooms into the tropical western  
208 Pacific (left) where the OH hole (smaller than 1 molec./cm<sup>3</sup>) exists and the adjacent Indian Ocean (right)  
209 regions. The OH hole in the western Pacific has already been identified (Rex et al., 2014). However, similar  
210 values of OH in other tropical ocean regions are not reported and are rare, although OH concentrations  
211 generally decrease with latitude from tropics to the high latitudes. The OH concentrations are largest in the  
212 tropical latitudes and along the shipping routes (e.g. Gopikrishnan and Kuttippurath, 2021), and they  
213 gradually decrease from 30°–40° N/S to the polar regions. Since the tropical upwelling regions transport  
214 atmospheric trace gases to the middle latitudes of stratosphere, the changes in OH concentrations in these

215 latitudes are very important. Fig. 1 (bottom, right) shows an OH minimum in Indian Ocean located at 6°–  
216 14°N and 92°–95°E, which could also be termed as a “remote” extension of the western Pacific OH hole as  
217 the Indian Ocean minimum region is in its vicinity. High reactivity of OH, about a second, is the reason for  
218 its short life span, which makes OH highly variable in time and space. Changes in the concentration of OH  
219 depend on various environmental factors such as humidity and cloudiness, intensity of incoming radiation  
220 and the presence of natural or anthropogenic pollutants (Lelieveld et al., 2004).

221  
222 The monthly mean OH analysed for the past 14 years (2005–2018) is shown in Fig. 2 (top). The analysis  
223 indicates that the minimum values are spreading towards the west during the months of November,  
224 December, January and February. The minimum values are confined to a small region in this period. The  
225 OH concentration increases in the western Bay of Bengal (BoB, 8°–18°N, 76°–90°E) afterwards in March  
226 and April. The OH minimum confines to a small region in May, June, July and August, and the minimum  
227 region (6°–18°N and 80°–100°E) is surrounded by high values (e.g.  $150\text{--}300 \times 10^4$  molec./cm<sup>3</sup>). The trough  
228 of minimum is observed at a specific location and it is consistently present in all months, at 6°–14°N and  
229 92°–95°E, and the minimum region is found around the Andaman and Nicobar Islands in the northeast  
230 Indian Ocean. We analysed another data (CAM5) for the period 2003–2018, which also displayed a very  
231 similar monthly cycle (unit of OH concentration is different here) with a region of OH minimum around 6°–  
232 18°N and 80°–100°E, as found in the TES data (Supplemental Fig. 1).

233  
234 Fig. 2 (bottom) shows the monthly OH minimum in the selected latitude-longitude region (6°–18°N and  
235 80°–100°E) averaged for the period 2005–2018. It shows two minima in a year, with the smallest values in  
236 April ( $15 \times 10^4$  molec./cm<sup>3</sup>) and a secondary minimum during September–November ( $18 \times 10^4$  molec./cm<sup>3</sup>),  
237 depending on year (here in November). Relatively higher values are observed in other months, about 20–  
238  $40 \times 10^4$  molec./cm<sup>3</sup>. We also analysed the CAM5 data to investigate the seasonal distribution of OH

239 minimum, as shown in Fig. 2. The results show very similar monthly progression with the annual minimum  
240 in April (0.012 ppt) and the secondary minimum in September–November (0.015 ppt), as found in the TES  
241 reanalysis. It suggests that, although the OH minimum zone is vast and spread across hundreds of  
242 kilometers, the lowest values of OH appears in April. Henceforth, the OH minimum in Indian Ocean is  
243 seasonal and is in a relatively small region as compared to that in the western Pacific. This situation  
244 demands a detailed analysis of OH distribution in different seasons over Indian Ocean.

245

### 246 *3.2 Seasonal Variability of OH minimum*

247 Fig. 3 displays the minimum values of OH in the latitude region 4°–20° N for different seasons. Although  
248 the seasonal change is very small in the selected region, comparatively lower values are found in spring  
249 (MAM, about  $15 \times 10^4$  molec./cm<sup>3</sup>), consistent with our previous discussion. On the other hand, the basin-  
250 wide lowest values ( $< 100 \times 10^4$  molec./cm<sup>3</sup>) are found in winter (DJF) and autumn (SON), but relatively  
251 higher values ( $> 200 \times 10^4$  molec./cm<sup>3</sup>) outside the minimum region are found in summer and spring,  
252 particularly in the western BoB. We also examined the longitudinal distribution of OH in the selected region  
253 (Fig. 3, top) and it shows the smallest values ( $20 \times 10^4$  molec./cm<sup>3</sup>) at 92°–95° E, which coincides the  
254 selected OH minimum region, where the seasonal differences are very small. However, beyond this  
255 minimum region (92°–95° E), the lowest OH values are found in winter and autumn. The CAMS data also  
256 yield a similar seasonal distribution of OH in BoB and in the selected region (Supplemental Fig. 2). In fact,  
257 the most critical element of OH distribution is its diurnal variation (Prinn et al., 1995). It quickly responds  
258 to solar radiation and reaches its peak concentration at noon, as the photolysis of O<sub>3</sub> to O(<sup>1</sup>D) depends on  
259 solar radiation, and the reaction between O(<sup>1</sup>D) and H<sub>2</sub>O is the key source for OH (Rohrer and Berresheim,  
260 2006). Additionally, the diurnal variation (TES data presented are monthly) depends on seasons, as the  
261 intensity of solar radiation at noon is stronger and duration of day is longer in summer. Accordingly,  
262 concentrations of OH are higher in summer than that in winter (Lu et al., 1991), as found in our analyses.

263 Fig. 4 displays OH (from CAMS), precipitation, SST, cloud cover, SO<sub>2</sub>, CO and NO<sub>x</sub> for different seasons in  
264 2005. In winter, there are lower SST and less precipitation in the northern BoB, above 8° N, and are  
265 relatively higher south of that latitude. The OH production is expected to decrease under these  
266 temperature conditions and consequently, its concentration is relatively lower during this season. In April,  
267 the temperature and SST increase (highest SST in the annual cycle) and thus, higher values of OH can be  
268 found in the western BoB, but the annual minimum is observed during this period in the eastern BoB.  
269 Furthermore, the winds make a circular pattern around the minimum region north of 6° N. In summer,  
270 heavy rainfall is observed at the east coast of BoB, about 20–30 mm. SST is also relatively high in the  
271 northern and southeastern BoB. Therefore, OH shows the highest annual concentrations over the basin in  
272 this period. The largest OH concentrations are found in the lowest precipitation regions such as 6° N along  
273 the meridional transect of BoB, and thus, the OH minimum region shrinks to its smallest in the annual cycle  
274 during this period. In autumn, SST of these regions is relatively small, providing a condition for  
275 correspondingly large OH minimum zone there.

276  
277 Reaction of OH radical in cloud water play an important role in the formation of secondary aerosols. Strong  
278 seasonal cycle is observed in cloud fraction over Indian Ocean, where very high values are observed in  
279 summer and autumn (0.8–1), but relatively small fraction of clouds in winter and spring (< 0.5). Similar  
280 seasonal distribution is also observed in the region of OH minimum, where the highest cloud fractions are  
281 found in summer and autumn, and smallest in winter. However, the analysis shows that the impact of  
282 clouds on the smallest OH values in the minimum region is limited.

283  
284 Since there is an active volcano in the Andaman Islands, we also examined the concentration of SO<sub>2</sub> in the  
285 region as it is a sink for atmospheric SO<sub>2</sub> (third panel from bottom). In general, relatively large  
286 concentrations are observed in the Indian coastal regions, where the seasonal highest values are observed

287 in spring ( $3\text{--}4\ \mu\text{g}/\text{m}^3$ ). The values are very small over the open ocean, but relatively high  $\text{SO}_2$  concentrations  
288 are found in the OH minimum region, which is present throughout the year. The seasonal differences are  
289 very small and therefore, there are other factors controlling the OH minimum in this region. Biomass  
290 burning produces a large amount of CO in earth's atmosphere, mostly within 2 km. Lu et al. (1993) showed  
291 that the decrease of CO implies an increase of OH (Reaction R8). In general, the amount of CO is high during  
292 winter, which decreases as summer arrives. The highest concentration of CO is observed in winter and then  
293 in autumn, and the smallest in summer. Furthermore, ozone is the primary precursor of OH radical and  
294 therefore, the changes in ozone decides the distribution of OH in the atmosphere. The ozone distribution  
295 also follows the distribution of CO, as it shows basin-wide high concentration in winter and autumn, and  
296 low values in summer and spring (Supplemental Fig. 3). The minimum ozone is also found in the same  
297 region of OH minimum in spring; consistent with that found in the western Pacific (Rex et al., 2014).  
298 However, there are still some other processes that could drive the seasonal OH minimum in Indian Ocean,  
299 as the meteorology or ocean state are not enough to explain this. Therefore, we explore the changes in  
300 tropospheric chemistry to find the additional causative factors.

301  
302 Being the major oxidant in the troposphere, the distribution of OH radical is connected to several trace  
303 gases in the atmosphere. We analysed the monthly average of OH and its source/sink trace gases in the  
304 selected region and are displayed in Fig. 5. The OH distribution shows its highest values in summer (June,  
305 July and August), which decrease gradually with time until April. The smallest values are observed in winter  
306 and spring (December through April). The fire counts and CO distribution follow similar temporal  
307 progression until September, as biomass burning is a major source for CO, and OH shows smaller values  
308 during the periods of high CO concentrations. Similarly, one of the mechanisms by which OH is lost is its  
309 reaction with  $\text{NO}_2$  under high  $\text{NO}_x$  conditions. The formation of  $\text{HNO}_3$  normally indicates the reaction of OH  
310 with  $\text{NO}_2$  and the loss of OH (i.e., R10); a reason for the opposite monthly distribution of  $\text{NO}_2$  and OH here.

311 Besides, the distribution of OH radical is associated with certain other trace gases such as HONO, CH<sub>4</sub> and  
312 HCHO, and changes in the concentration of those could also make analogous variation in OH distribution,  
313 as illustrated in the figure. The trace gases that are the sink of OH show an opposite distribution to that of  
314 OH, as illustrated by CH<sub>4</sub>, CO and SO<sub>2</sub>, but show the lowest values in April during the annual OH minimum.  
315 Seasonal variability of OH depends on a number of factors, such as the changes in solar radiation and the  
316 amount of water vapor, as H<sub>2</sub>O has a major role in the production of OH radicals (e.g. see the temporal  
317 distribution of H<sub>2</sub>O in the figure). The primary production of OH by photolysis of ozone happens in the  
318 presence of water vapour. In addition, photolysis of H<sub>2</sub>O at wavelength in first continuum is an alternate  
319 source for the production of OH radical (Ung and Back, 1964):



321 As shown by Lu et al. (1991), in an unpolluted troposphere, 50% of OH is generated by the reaction between  
322 H<sub>2</sub>O and O (<sup>1</sup>D) as the direct source, as demonstrated in the figure.

323

### 324 ***3.3 Inter-annual variability of OH minima***

325 Interannual variability of global OH concentration is mainly connected to the El Niño Southern Oscillation  
326 (ENSO) events. Periods of La Niña are positively correlated with an increase in OH. This correlation is due  
327 to the increased occurrence of lightning emission of NO<sub>x</sub> during La Niña owing to more convective activity  
328 during the period (Turner et. al., 2018). Biomass burning related CO emissions is another event, which may  
329 also trigger the variability of OH in the atmosphere. Since Southeast Asia is a zone of biomass burning, the  
330 interannual variability of OH can be highly influenced by these fire events. In general, biomass burning is  
331 episodically restricted and it peaks during March–April in Southeast Asia (Huang et al., 2013; Kuttippurath  
332 et al., 2020), as exhibited in the fire counts data in Fig. 5.

333

334 Fig. 6 shows the interannual variability of OH in its minimum zone for the period 2005–2018. The spatial  
335 variation of OH (averaged values are shown in the top panel and minimum values in the second panel from  
336 the top; averaged over 90°–98°E) for different years are depicted. The black contours indicate  $20 \times 10^4$   
337 molec./cm<sup>3</sup>. The OH climatology over the region shows a consistent pattern of OH minimum in Indian  
338 Ocean. The seasonal minimum of OH in spring is clearly visible with concentrations of about  $15 \times 10^4$   
339 molec./cm<sup>3</sup> between 8° and 14° N, and the lowest around 12° N. On the other hand, high OH concentrations  
340 are observed at 5°–8° N and north of 14° N ( $> 200 \times 10^4$  molec./cm<sup>3</sup>). Since this is the monthly climatology,  
341 the interannual changes are hardly visible. Therefore, we also examined the minimum values of each month  
342 (second panel from the top). The analyses show the lowest OH concentrations between 10° and 13° N, and  
343 are below  $20 \times 10^4$  molec./cm<sup>3</sup>. The latitude regions north and south of these seasonal minima show OH  
344 values of about  $50$ – $100 \times 10^4$  molec./cm<sup>3</sup>. The highest OH values are observed beyond these minima zones,  
345 i. e. at 7°–5° N and 17°–19°, about  $200 \times 10^4$  molec./cm<sup>3</sup> or higher. The inter-annual changes are very large  
346 and explicit in these analyses. For instance, the minimum values are found in relatively smaller regions in  
347 2005, 2011 and 2012.

348  
349 To diagnose the characteristics of minimum region and its year-to-year changes, we found the average  
350 values in each month for the minimum region and are shown in the bottom four panels. The lowest  
351 minimum in the TES data is observed in 2009 and 2016 (around  $60 \times 10^4$  molec./cm<sup>3</sup>), and the yearly minima  
352 are in the range of  $40$ – $60 \times 10^4$  molec./cm<sup>3</sup>. In general, the minimum peaks are found in spring. CO emitted  
353 from biomass burning might have caused this variability, as this is the peak biomass burning season in South  
354 Asia (Huang et al., 2013). Conversely, high values are observed in December and January, and even the  
355 minimum trough was absent in 2010. As mentioned earlier, the inter-annual variability of ozone and CO is  
356 highly connected to ENSO events (e.g. Xue et al., 2021). Therefore, there is a strong relationship between  
357 ENSO events and OH minimum. In most years, we find higher values of OH during La Niña periods. For



358 instance, the year 2010 had a strong La Niña, which could be the reason for the absence of OH minimum  
359 in that year. Since H<sub>2</sub>O is a source for OH, its monthly and yearly distributions are in agreement with those  
360 of H<sub>2</sub>O. Conversely, as CO, SO<sub>2</sub> and CH<sub>4</sub> are known to be the sink of OH, their monthly and yearly  
361 distributions are opposite to those of OH, except in the annual minimum period of April. These analyses  
362 also expose relatively high values of OH from 2015 onwards, which can be due to the slight reduction in its  
363 sink (three bottom panels).

364

### 365 *3.4 Comparison with the western Pacific OH minimum*

366 An OH minimum or OH hole has already been reported in the tropical western Pacific. Very small values of  
367 ozone in this region (i.e. clean air) is the main reason for this (Rex et al., 2014). Tropical pacific is the major  
368 source/pathway of trace gases to the stratosphere and thus, the region has a great significance in terms of  
369 atmospheric composition. Here, we compare the OH hole in the Pacific with the Indian Ocean OH minimum,  
370 as it is adjacent to the Pacific Ocean that plays a key role in stratospheric and tropospheric exchange of  
371 trace gases. Fig. 7 shows the OH minimum values in Indian and Pacific Oceans for each month from 2005  
372 to 2018. It is evident that the western Pacific OH minimum is small enough to call a “hole” and is present  
373 throughout the year. In contrast, the OH minimum in Indian Ocean is seasonal, where the lowest values  
374 appear in April. As mentioned, the lowest OH minimum in Indian Ocean is about  $10\text{--}20 \times 10^5$  molec./cm<sup>3</sup>,  
375 depending on month and year. The CAMS data (dashed lines) replicate the monthly and interannual  
376 variability of OH minimum in both oceanic regions, as demonstrated with the TES data.

377

### 378 *3.5 Modelled OH minimum*

379 To examine the existence of OH minimum, we simulated the distribution of OH in the Indian and Pacific  
380 Oceans using the WACCM model (Fig. 8). The model reproduces the general features of OH distribution  
381 across the latitudes, with the highest concentrations in the tropics, which decreases with latitude towards

382 the poles. The model shows the highest values in summer (June–September) and the smallest in autumn,  
383 winter and spring (in March), as for the TES data. Therefore, the seasonal cycle shows the highest values in  
384 summer and spring, and the smallest in winter and autumn, as found with the TES data outside the OH  
385 minimum region (Supplemental Fig. 4). However, the model hardly finds the seasonal minimum in the  
386 selected region, where the annual minimum is as it is found for the other regions over the basin. The  
387 simulations for different years and for the western Pacific (Supplemental Fig. 5) indicate that the model  
388 struggles to capture the OH hole, although there is a seasonal minimum in winter as over Indian Ocean.  
389 Horizontal resolution of the model can be one of the primary reasons for this difference, although different  
390 chemical reactions, representation of photolysis of O<sub>3</sub>, and the modelled results of ozone and CO play a  
391 decisive role in simulating OH values by the model (e.g. Nicely et al., 2017). Since OH minima or hole are  
392 extreme values, simulating this atmospheric chemistry would be a great challenge for any CTM. Therefore,  
393 dedicated model studies are required to infer the simulations of such extreme cases. This is a future study  
394 as the model sensitivity assessment is beyond the scope of this work.

395

### 396 ***3.6 Limitation of the study***

397 This study is based on the reanalysed data as there are no direct measurements from *in situ* instruments or  
398 satellites in the region concerned. Since these data are heavily weighted by the simulations from a model  
399 that used for making the reanalysis, our assessment with the same also has this particular limitation,  
400 because modelling of OH is challenging and many uncertainties are still there (e.g. Nicely et al., 2018). This  
401 is the reason that we used two different reanalysed data sets here. In addition, we have also used model  
402 results for examining the representation of OH minimum in CTMs. The region in which the OH minimum  
403 has found is around the Andaman and Nicobar Islands and there is an active volcano on the island. This  
404 suggests that the island land mass also has a role in the particular distribution OH there. Our study reiterate

405 the need of more OH and related trace gas measurements in the region for a solid conclusion about the  
406 OH minimum over Indian Ocean.

407

#### 408 4. Conclusions

409 The OH distribution over Indian Ocean exhibits two minima, in spring and autumn, as assessed from the  
410 TES and CAMS reanalyses. The spring concentrations reach to  $15 \times 10^4$  molec./cm<sup>3</sup> and slightly higher in  
411 autumn (SON). The minimum region is found near the Andaman and Nicobar Islands in Indian Ocean, where  
412 it houses an active volcano. The concentration of SO<sub>2</sub> is relatively higher there, which is also the only region  
413 over BoB with high SO<sub>2</sub> concentrations, except near the coasts. Since SO<sub>2</sub> is one of the sinks of OH, this  
414 could be a reason for the OH minimum there. In general, the sink trace gases (e.g. CO, SO<sub>2</sub> and CH<sub>4</sub>) show  
415 an opposite temporal distribution to that of OH in the minimum region. The minimum troughs were present  
416 in all years, except in the strong La Niña year 2010. The OH distribution shows an anti-correlation with ENSO  
417 events, and therefore, relatively higher OH concentrations are found during the La Niña years. The analyses  
418 also reveal that the biomass burning and CO distribution have significant influence on the distribution of  
419 OH minimum, as the OH chemistry is closely linked to the changes in O<sub>3</sub>, CO and HNO<sub>3</sub>. The model struggles  
420 to capture the OH minimum in both oceans, which demand more dedicated studies with high resolution  
421 simulations. In brief, the OH minimum in the western Pacific Ocean is owing to its clean air there, but it is  
422 very likely due to the polluted air over Indian Ocean. As OH has the control on the cleansing capacity of  
423 atmosphere, its changes will affect air quality and troposphere-stratosphere exchange, which in turn, would  
424 affect public and ecosystem health, and climate of the region. Therefore, this study suggests a continuous  
425 monitoring of atmospheric OH over Indian Ocean.

426

427

428

429 **Credit authorship contribution statement**

430 **JK:** Conceptualization, Methodology, Supervision, Visualization, Writing-original draft, review & editing of  
431 the original draft, **AD, SR, WF:** Methodology, Data Analysis, Visualization, Writing - original draft

432

433 **Acknowledgement**

434 We thank the Director, Indian Institute of Technology Kharagpur (IIT Kgp), Chairman of CORAL IIT Kgp and  
435 the Ministry of Education (MoE) for facilitating the study. We thank Indian Institute of Technology  
436 Kharagpur, Ministry of Education (MoE), Naval Research Board (OEP), Defence Research Development  
437 Organisation, National Centre for Ocean Information Services (INCOIS) Hyderabad and Ministry of Earth  
438 Science (MoES) for facilitating and partly funding the study. JK acknowledges his gratitude to V K Patel and  
439 G S Gopikrishnan for their help with the data analysis. We thank the scientific organisations and scientists  
440 who made available the TES and CAMS reanalyses, TRMM precipitation, ERSST and ENSO index data for this  
441 study. The TMPA data were provided by the NASA/Goddard Space Flight Center's Mesoscale Atmospheric  
442 Processes Laboratory and PPS, which develop and compute the TMPA as a contribution to TRMM.

443 **Data availability**

444 The data used in this study are publicly available.

445 TES chemical reanalyses : <https://tes.jpl.nasa.gov/chemical-reanalysis/>,

446 TRMM on [http:// mirador.gsfc.nasa.gov/cgi-bin/mirador/](http://mirador.gsfc.nasa.gov/cgi-bin/mirador/)

447 ERSST data: <https://www1.ncdc.noaa.gov/pub/data/cmb/ersst/v5/netcdf/>.

448 MERRA 2 data are available on: <https://giovanni.gsfc.nasa.gov/giovanni/>

449 The CAMS data are available on: <https://ads.atmosphere.copernicus.eu/#!/search?text=reanalysis>

450 MODIS fire count data: [https://firms.modaps.eosdis.nasa.gov/active\\_fire/](https://firms.modaps.eosdis.nasa.gov/active_fire/)

451

452 **Additional Information**

453 **Declaration**

454 The authors confirm that there are no known conflicts of interest associated with this article.

455 **Competing Interest**

456 The authors declare no competing interest.

457 **References**

458 Anandh, T.S., Das, B.K., Kumar, B., Kuttippurath, J., Chakraborty, A., 2018. Analyses of the oceanic heat  
459 content during 1980–2014 and satellite-era cyclones over Bay of Bengal. *Int. J. Climatol.* 38, 5619–  
460 5632. <https://doi.org/10.1002/JOC.5767>

461 Cady-Pereira, K.E., Payne, V.H., Neu, J.L., Bowman, K.W., Miyazaki, K., Marais, E.A., Kulawik, S., Tzompa-  
462 Sosa, Z.A., Hegarty, J.D., 2017. Seasonal and spatial changes in trace gases over megacities from  
463 Aura TES observations: Two case studies. *Atmos. Chem. Phys.* 17, 9379–9398.  
464 <https://doi.org/10.5194/ACP-17-9379-2017>

465 Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A.,  
466 Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol,  
467 C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E. V., Isaksen,  
468 L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park,  
469 B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N., Vitart, F., 2011. The ERA-Interim  
470 reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.*  
471 137, 553–597. <https://doi.org/10.1002/QJ.828>

472 Deeter, M.N., Emmons, L.K., Francis, G.L., Edwards, D.P., Gille, J.C., Warner, J.X., Khattatov, B., Ziskin, D.,

473 Lamarque, J.F., Ho, S.P., Yudin, V., Attié, J.L., Packman, D., Chen, J., Mao, D., Drummond, J.R., 2003.  
474 Operational carbon monoxide retrieval algorithm and selected results for the MOPITT instrument. *J.*  
475 *Geophys. Res. Atmos.* 108, 4399. <https://doi.org/10.1029/2002JD003186>

476 Elshorbany, Y., Barnes, I., Becker, K.H., Kleffmann, J., Wiesen, P., 2010. Sources and cycling of  
477 tropospheric hydroxyl radicals - An overview. *Zeitschrift fur Phys. Chemie* 224, 967–987.  
478 <https://doi.org/10.1524/ZPCH.2010.6136/MACHINEREADABLECITATION/RIS>

479 Giglio, L., Descloitres, J., Justice, C.O., Kaufman, Y.J., 2003. An Enhanced Contextual Fire Detection  
480 Algorithm for MODIS. *Remote Sens. Environ.* 87, 273–282. [https://doi.org/10.1016/S0034-](https://doi.org/10.1016/S0034-4257(03)00184-6)  
481 [4257\(03\)00184-6](https://doi.org/10.1016/S0034-4257(03)00184-6)

482 Gopikrishnan, G.S., Kuttippurath, J., 2021. A decade of satellite observations reveal significant increase in  
483 atmospheric formaldehyde from shipping in Indian Ocean. *Atmos. Environ.* 246, 118095.  
484 <https://doi.org/10.1016/J.ATMOSENV.2020.118095>

485 Huang, B., Thorne, P.W., Banzon, V.F., Boyer, T., Chepurin, G., Lawrimore, J.H., Menne, M.J., Smith, T.M.,  
486 Vose, R.S., Zhang, H.M., 2017. Extended Reconstructed Sea Surface Temperature, Version 5  
487 (ERSSTv5): Upgrades, Validations, and Intercomparisons. *J. Clim.* 30, 8179–8205.  
488 <https://doi.org/10.1175/JCLI-D-16-0836.1>

489 Huang, K., Fu, J.S., Hsu, N.C., Gao, Y., Dong, X., Tsay, S.C., Lam, Y.F., 2013. Impact assessment of biomass  
490 burning on air quality in Southeast and East Asia during BASE-ASIA. *Atmos. Environ.* 78, 291–302.  
491 <https://doi.org/10.1016/J.ATMOSENV.2012.03.048>

492 Inness, A., Baier, F., Benedetti, and the MACC team., 2013. The MACC reanalysis: an 8 yr data set of  
493 atmospheric composition. *Atmos. Chem. Phys.* 13, 4073–4109, [https://doi.org/10.5194/acp-13-](https://doi.org/10.5194/acp-13-4073-2013)  
494 [4073-2013](https://doi.org/10.5194/acp-13-4073-2013).

495 Inness, A., Ades, M., Agustí-Panareda, A., Barr, J., Benedictow, A., Blechschmidt, A.M., Jose Dominguez, J.,  
496 Engelen, R., Eskes, H., Flemming, J., Huijnen, V., Jones, L., Kipling, Z., Massart, S., Parrington, M.,  
497 Peuch, V.H., Razinger, M., Remy, S., Schulz, M., Suttie, M., 2019. The CAMS reanalysis of  
498 atmospheric composition. *Atmos. Chem. Phys.* 19, 3515–3556. [https://doi.org/10.5194/ACP-19-](https://doi.org/10.5194/ACP-19-3515-2019)  
499 [3515-2019](https://doi.org/10.5194/ACP-19-3515-2019)

500 King, M.D., Menzel, W.P., Kaufman, Y.J., Tanré, D., Gao, B.C., Platnick, S., Ackerman, S.A., Remer, L.A.,  
501 Pincus, R., Hubanks, P.A., 2003. Cloud and aerosol properties, precipitable water, and profiles of  
502 temperature and water vapor from MODIS. *IEEE Trans. Geosci. Remote Sens.* 41, 442–456.  
503 <https://doi.org/10.1109/TGRS.2002.808226>

504 Kuttippurath, J., Murasingh, S., Stott, P.A., Balan Sarojini, B., Jha, M.K., Kumar, P., Nair, P.J., Varikoden, H.,  
505 Raj, S., Francis, P.A., Pandey, P.C., 2021. Observed rainfall changes in the past century (1901–2019)  
506 over the wettest place on Earth. *Environ. Res. Lett.* 16, 024018. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/ABC78)  
507 [9326/ABC78](https://doi.org/10.1088/1748-9326/ABC78)

508 Kuttippurath, J., Singh, A., Dash, S.P., Mallick, N., Clerbaux, C., Van Damme, M., Clarisse, L., Coheur, P.F.,  
509 Raj, S., Abhishek, K., Varikoden, H., 2020. Record high levels of atmospheric ammonia over India:  
510 Spatial and temporal analyses. *Sci. Total Environ.* 740, 139986.  
511 <https://doi.org/10.1016/j.scitotenv.2020.139986>

512 Lelieveld, J., Dentener, F.J., Peters, W., Krol, M.C., 2004. On the role of hydroxyl radicals in the self-  
513 cleansing capacity of the troposphere. *Atmos. Chem. Phys.* 4, 2337–2344.  
514 <https://doi.org/10.5194/ACP-4-2337-2004>

515 Lelieveld, J., Gromov, S., Pozzer, A., Taraborrelli, D., 2016. Global tropospheric hydroxyl distribution,  
516 budget and reactivity. *Atmos. Chem. Phys.* 16, 12477–12493. [https://doi.org/10.5194/ACP-16-](https://doi.org/10.5194/ACP-16-12477-2016)  
517 [12477-2016](https://doi.org/10.5194/ACP-16-12477-2016)

518 Levy, H., 1971. Normal Atmosphere: Large Radical and Formaldehyde Concentrations Predicted. *Science*  
519 (80-. ). 173, 141–143. <https://doi.org/10.1126/SCIENCE.173.3992.141>

520 Livesey, N. J. et al.: EOS MLS Version 4.2x Level 2 data quality and description document (Revision E),  
521 2020. Tech. Rep., Jet Propulsion Laboratory, available at: [https://mls.jpl.nasa.gov/eos-aura-](https://mls.jpl.nasa.gov/eos-aura-mls/data-documentation)  
522 [mls/data-documentation](https://mls.jpl.nasa.gov/eos-aura-mls/data-documentation) (last access: 29 September, 2021), (data available at:  
523 <https://disc.gsfc.nasa.gov>, last access: 29 September 2021).

524 Lu, Y., Khalil, M.A.K., 1993. Methane and carbon monoxide in OH chemistry: The effects of feedbacks and  
525 reservoirs generated by the reactive products. *Chemosphere* 26, 641–655.  
526 [https://doi.org/10.1016/0045-6535\(93\)90450-J](https://doi.org/10.1016/0045-6535(93)90450-J)

527 Lu, Y., Khalil, M.A.K., 1991. Tropospheric OH: model calculations of spatial, temporal, and secular  
528 variations. *Chemosphere* 23, 397–444. [https://doi.org/10.1016/0045-6535\(91\)90194-I](https://doi.org/10.1016/0045-6535(91)90194-I)

529 Manning, M.R., Lowe, D.C., Moss, R.C., Bodeker, G.E., Allan, W., 2005. Short-term variations in the  
530 oxidizing power of the atmosphere. *Nat.* 2005 4367053 436, 1001–1004.  
531 <https://doi.org/10.1038/nature03900>.

532 Marsh, D., Mills, M., Kinnison, D. E., & Lamarque, J. -F., 2013. Climate change from 1850 to 2005  
533 simulated in CESM1(WACCM). *Journal Of Climate* 26, 7372-7391. doi:10.1175/JCLI-D-12-00558.1

534 Miyazaki, K., Bowman, K., 2017. Evaluation of ACCMIP ozone simulations and ozonesonde sampling biases  
535 using a satellite-based multi-constituent chemical reanalysis. *Atmos. Chem. Phys.* 17, 8285–8312.  
536 <https://doi.org/10.5194/ACP-17-8285-2017>

537 Miyazaki, K., Eskes, H.J., Sudo, K., 2015. A tropospheric chemistry reanalysis for the years 2005-2012  
538 based on an assimilation of OMI, MLS, TES, and MOPITT satellite data. *Atmos. Chem. Phys.* 15,  
539 8315–8348. <https://doi.org/10.5194/ACP-15-8315-2015>



540 Nicely, J. M., Salawitch, R. J., Canty, T., Anderson, D. C., Arnold, S. R., Chipperfield, M. P., et al., 2017.  
541 Quantifying the causes of differences in tropospheric OH within global models. *Journal of*  
542 *Geophysical Research: Atmospheres*, 122, 1983–2007. <https://doi.org/10.1002/2016JD026239>.

543 Nicely, J. M., Canty, T. P., Manyin, M., Oman, L. D., Salawitch, R. J., Steenrod, S. D., et al. (2018). Changes  
544 in global tropospheric OH expected as a result of climate change over the last several decades.  
545 *Journal of Geophysical Research: Atmospheres*, 123, 10,774–10,795.  
546 <https://doi.org/10.1029/2018JD028388>

547 Prinn, R.G., Weiss, R.F., Miller, B.R., Huang, J., Alyea, F.N., Cunnold, D.M., Fraser, P.J., Hartley, D.E.,  
548 Simmonds, P.G., 1995. Atmospheric Trends and Lifetime of CH<sub>3</sub>CCl<sub>3</sub> and Global OH Concentrations.  
549 *Science* (80-. ). 269, 187–192. <https://doi.org/10.1126/SCIENCE.269.5221.187>

550 Rex, M., Wohltmann, I., Ridder, T., Lehmann, R., Rosenlof, K., Wennberg, P., Weisenstein, D., Notholt, J.,  
551 Krüger, K., Mohr, V., Tegtmeier, S., 2014. A tropical West Pacific OH minimum and implications for  
552 stratospheric composition. *Atmos. Chem. Phys.* 14, 4827–4841. [https://doi.org/10.5194/ACP-14-](https://doi.org/10.5194/ACP-14-4827-2014)  
553 [4827-2014](https://doi.org/10.5194/ACP-14-4827-2014)

554 Rohrer, F., Berresheim, H., 2006. Strong correlation between levels of tropospheric hydroxyl radicals and  
555 solar ultraviolet radiation. *Nat.* 2006 4427099 442, 184–187. <https://doi.org/10.1038/nature04924>

556 Tropical Rainfall Measuring Mission (TRMM) (2011), TRMM (TMPA) Rainfall Estimate L3 3 hour 0.25  
557 degree x 0.25 degree V7, Greenbelt, MD, Goddard Earth Sciences Data and Information Services  
558 Center (GES DISC), Accessed: [Data Access Date], 10.5067/TRMM/TMPA/3H/7

559 Turner, A.J., Fung, I., Naik, V., Horowitz, L.W., Cohen, R.C., 2018. Modulation of hydroxyl variability by  
560 ENSO in the absence of external forcing. *Proc. Natl. Acad. Sci. U. S. A.* 115, 8931–8936.  
561 [https://doi.org/10.1073/PNAS.1807532115/SUPPL\\_FILE/PNAS.1807532115.SAPP.PDF](https://doi.org/10.1073/PNAS.1807532115/SUPPL_FILE/PNAS.1807532115.SAPP.PDF)

562 Ung, A.Y.-M., Back, R.A., 1964. The photolysis of water vapor and reactions of hydroxyl radicals. Can. J.  
563 Chem. 42, 753–763. <https://doi.org/10.1139/V64-114>

564 Vogel, B., Vogel, H., Kleffmann, J., Kurtenbach, R., 2003. Measured and simulated vertical profiles of  
565 nitrous acid—Part II. Model simulations and indications for a photolytic source. Atmos. Environ. 37,  
566 2957–2966. [https://doi.org/10.1016/S1352-2310\(03\)00243-7](https://doi.org/10.1016/S1352-2310(03)00243-7)

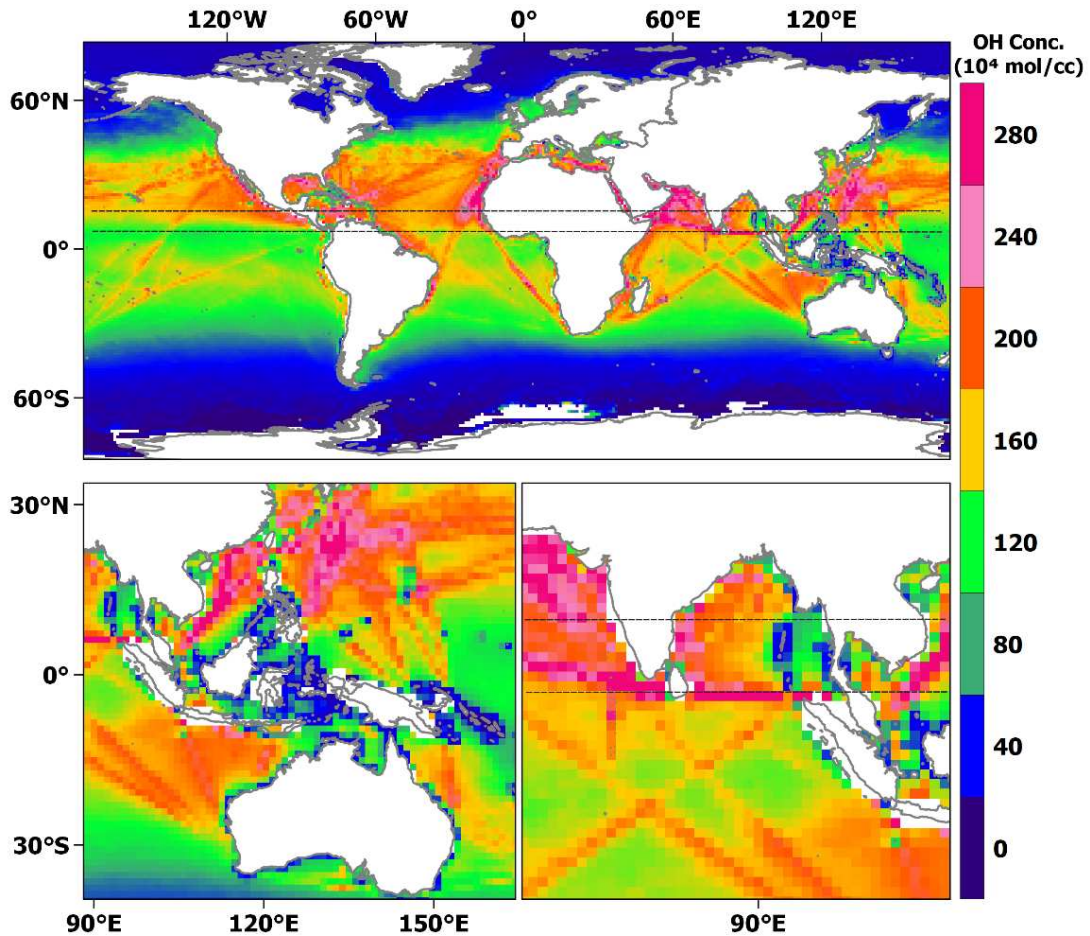
567 Wolfe, Glenn M., Nicely, J.M., Clair, J.M.S., Hanisco, T.F., Liao, J., Oman, L.D., Brune, W.B., Miller, D.,  
568 Thames, A., Abad, G.G., Ryerson, T.B., Thompson, C.R., Peischl, J., McCain, K., Sweeney, C.,  
569 Wennberg, P.O., Kim, M., Crouse, J.D., Hall, S.R., Ullmann, K., Diskin, G., Bui, P., Chang, C., Dean-  
570 Day, J., 2019a. Mapping hydroxyl variability throughout the global remote troposphere via synthesis  
571 of airborne and satellite formaldehyde observations. Proc. Natl. Acad. Sci. U. S. A. 166, 11171–  
572 11180. [https://doi.org/10.1073/PNAS.1821661116/SUPPL\\_FILE/PNAS.1821661116.SAPP.PDF](https://doi.org/10.1073/PNAS.1821661116/SUPPL_FILE/PNAS.1821661116.SAPP.PDF)

573 Wolfe, G M, Nicely, J.M., St.Clair, J.M., Hanisco, T.F., Liao, J., Oman, L., Brune, W.H., Miller, D.O., Thames,  
574 A.B., Abad, G.G., Ryerson, T.B., Peischl, J., McCain, K., Sweeney, C., Wennberg, P., Kim, M.J., Crouse,  
575 J.D., Hall, S.R., Ullmann, K., Diskin, G.S., Bui, T.P., Chang, C.S., Dean-Day, J.M., 2019b. ATom: Column-  
576 Integrated Densities of Hydroxyl and Formaldehyde in Remote Troposphere.  
577 <https://doi.org/10.3334/ORNLDAAC/1669>.

578 Wu J, Feng W, Liu H-L, Xue X, Marsh DR, Plane J., 2021. Self-consistent Global Transport of Metallic Ions  
579 with WACCM-X. Atmospheric Chemistry and Physics. 21, pp. 15619-15630

580 Xue, L., Ding, A., Cooper, O., Huang, X., Wang, W., Zhou, D., Wu, Z., McClure-Begley, A., Petropavlovskikh,  
581 I., Andreae, M.O., Fu, C., 2021. ENSO and Southeast Asian biomass burning modulate subtropical  
582 trans-Pacific ozone transport. Natl. Sci. Rev. 8. <https://doi.org/10.1093/NSR/NWAA132>

583



585

586 Fig. 1. The upper panel shows the global surface OH concentration for May 2009. The bottom panels

587 show the surface OH distribution over the western Pacific (left) and Indian (right) Oceans for May 2009.

588 The horizontal dotted lines demarcate the region of OH minimum in Indian Ocean and the lines extend

589 across the longitudes to examine any such areas in other oceanic regions.

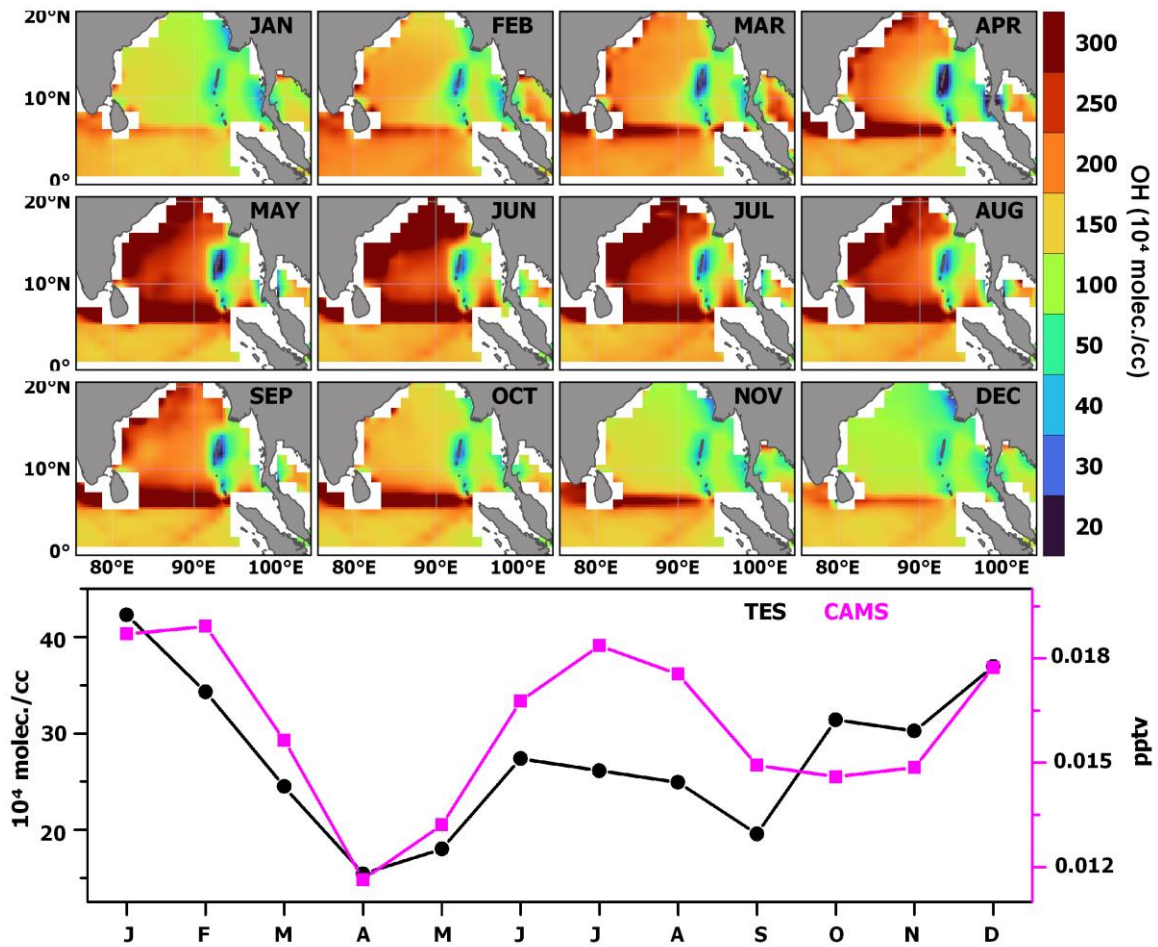
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596 Fig. 2. The monthly distribution of surface OH over the eastern north Indian Ocean for the period 2005–

597 2018. The regional average of monthly mean surface OH for the minimum region is illustrated in the bottom

598 panel. The months are represented by their first three letters in the top panel (e.g. JAN is January) and by

599 their first letter on the x-axis of bottom panel (e.g. J is for January and D is for December).

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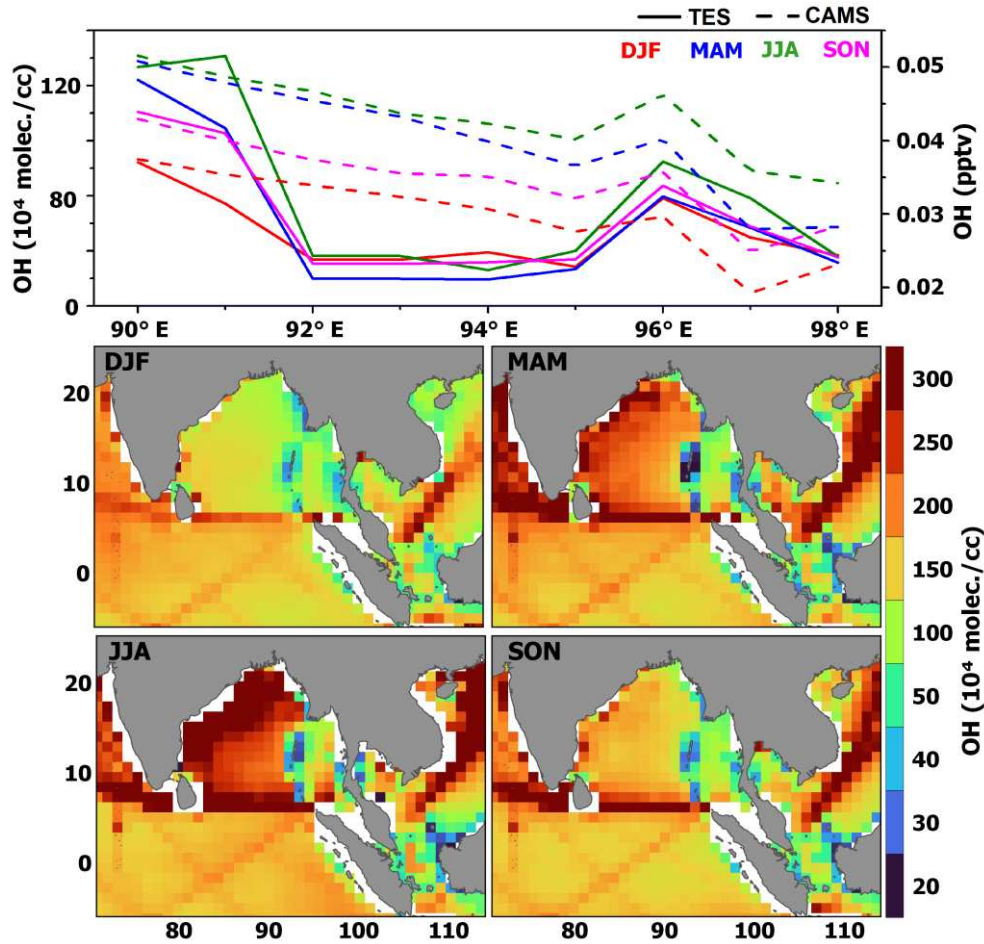
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607 Fig. 3. Top: distribution of surface OH averaged over the latitude band 4°–20° N (i.e. minimum region) for

608 different seasons. Bottom: distribution of surface OH averaged for each season for the period 2005–2018

609 in the eastern north Indian Ocean. The seasons are defined as winter (DJF), spring (MAM), summer (JJA)

610 and autumn (SON).

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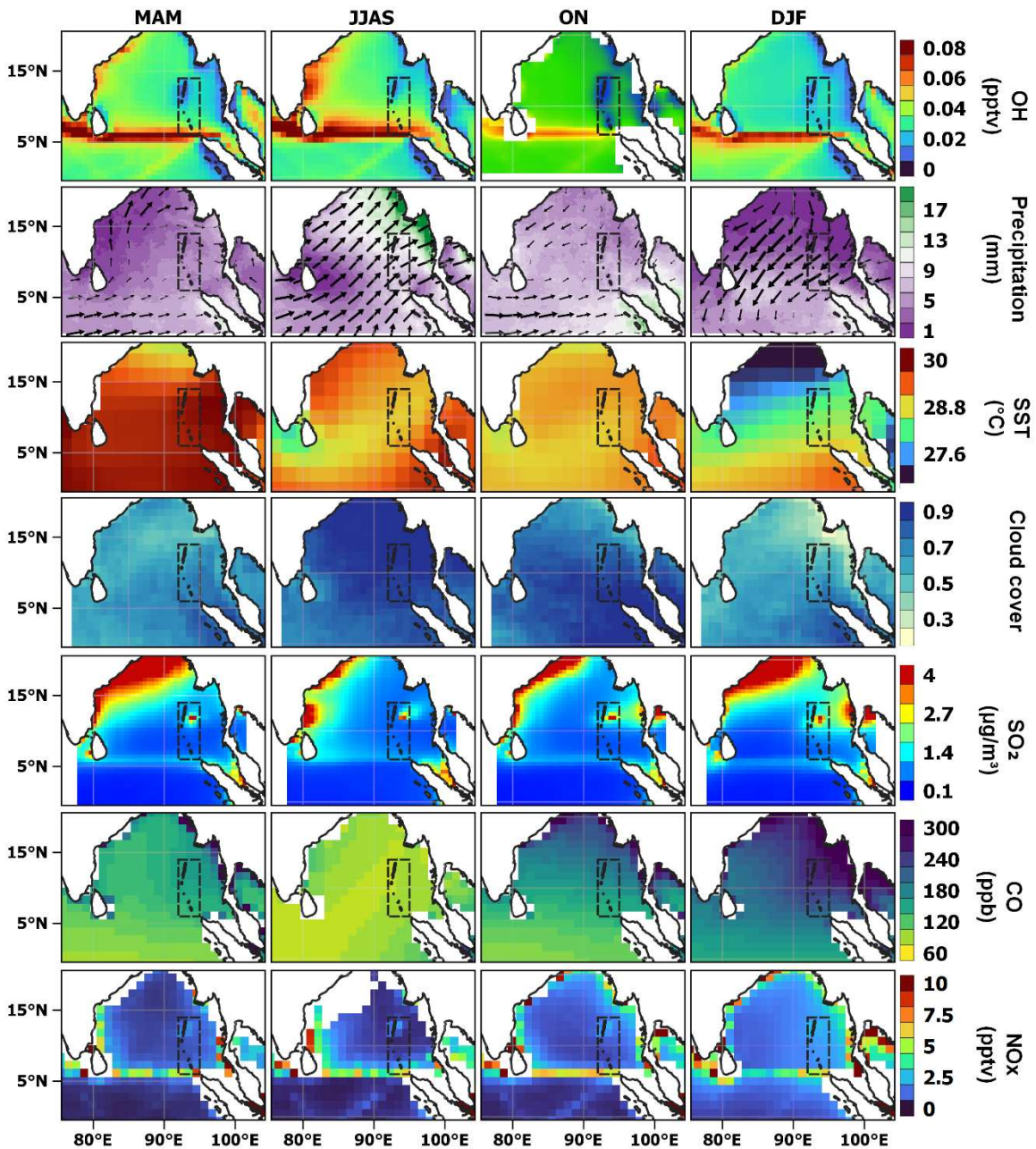
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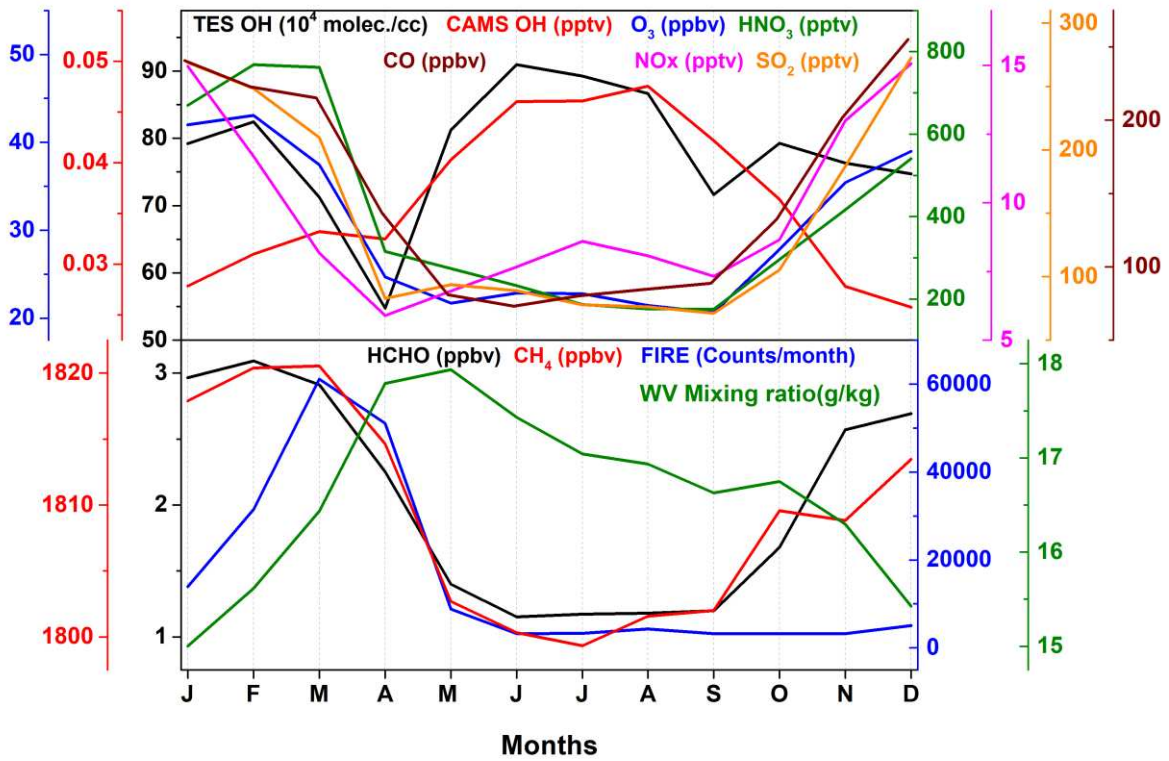
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619 Fig. 4. Surface concentration of OH from CAMS, precipitation (winds overlaid), SST, cloud cover, SO<sub>2</sub>, CO  
 620 and NO<sub>x</sub> for different seasons in eastern north Indian Ocean for the year 2005. The northern hemispheric  
 621 seasons are defined as winter (DJF), spring (MAM), summer (JJAS) and autumn (ON). Here, summer season  
 622 includes the month of September to examine the monsoon precipitation.

623



624

625 Fig. 5. Monthly distribution of surface OH and other trace gases averaged over the OH minimum region  
 626 (6°–14°N and 92°–95°E) for the period 2005–2018. The months are represented by their first letter on the  
 627 x-axis (e.g. J is for January and D is for December).

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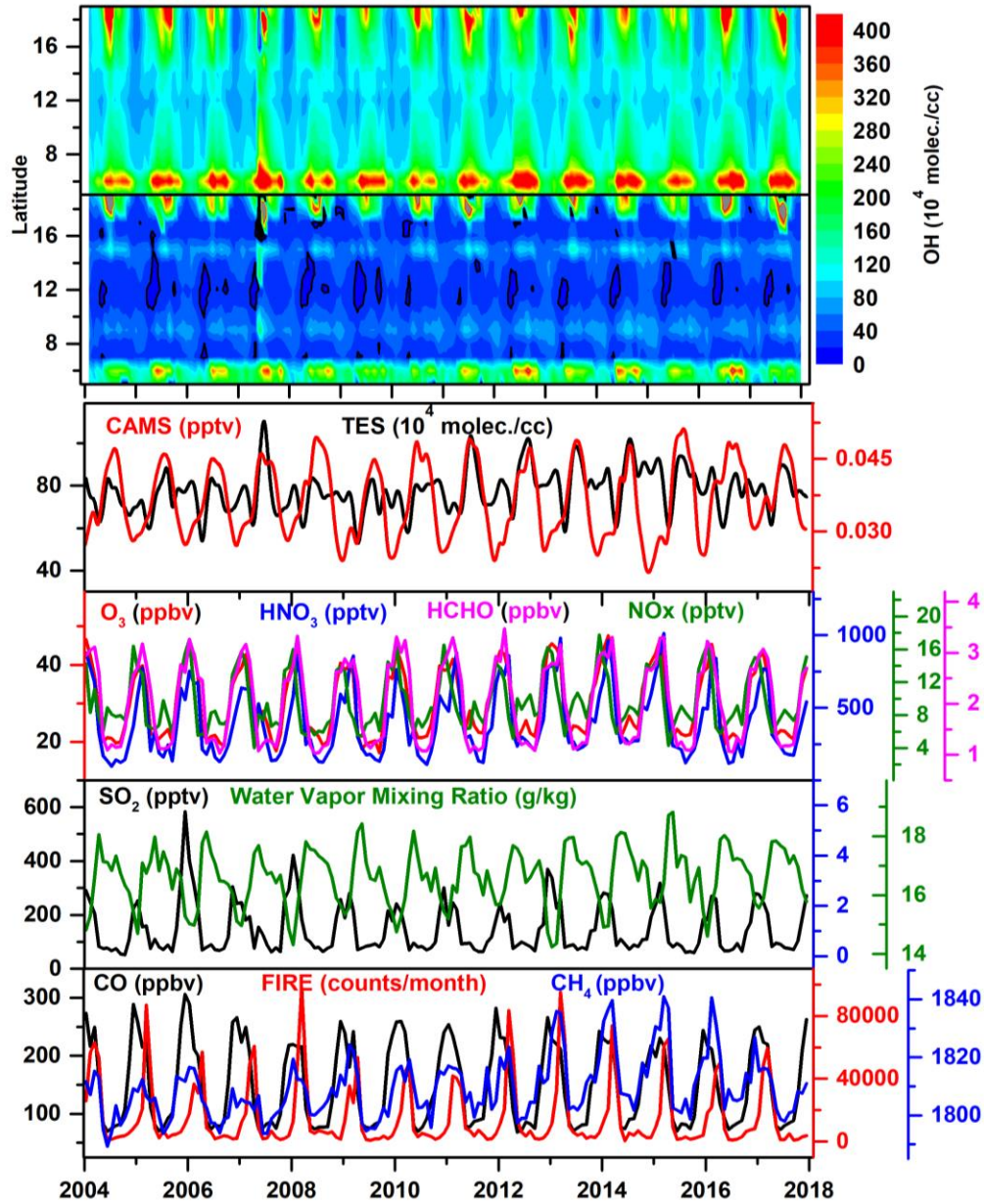
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636 **Fig. 6.** Surface OH concentration averaged over the longitudes 90°–98°E for the period 2005–2018. Here,

637 the top panel shows the average of surface OH (top) and the second panel from top shows the minimum

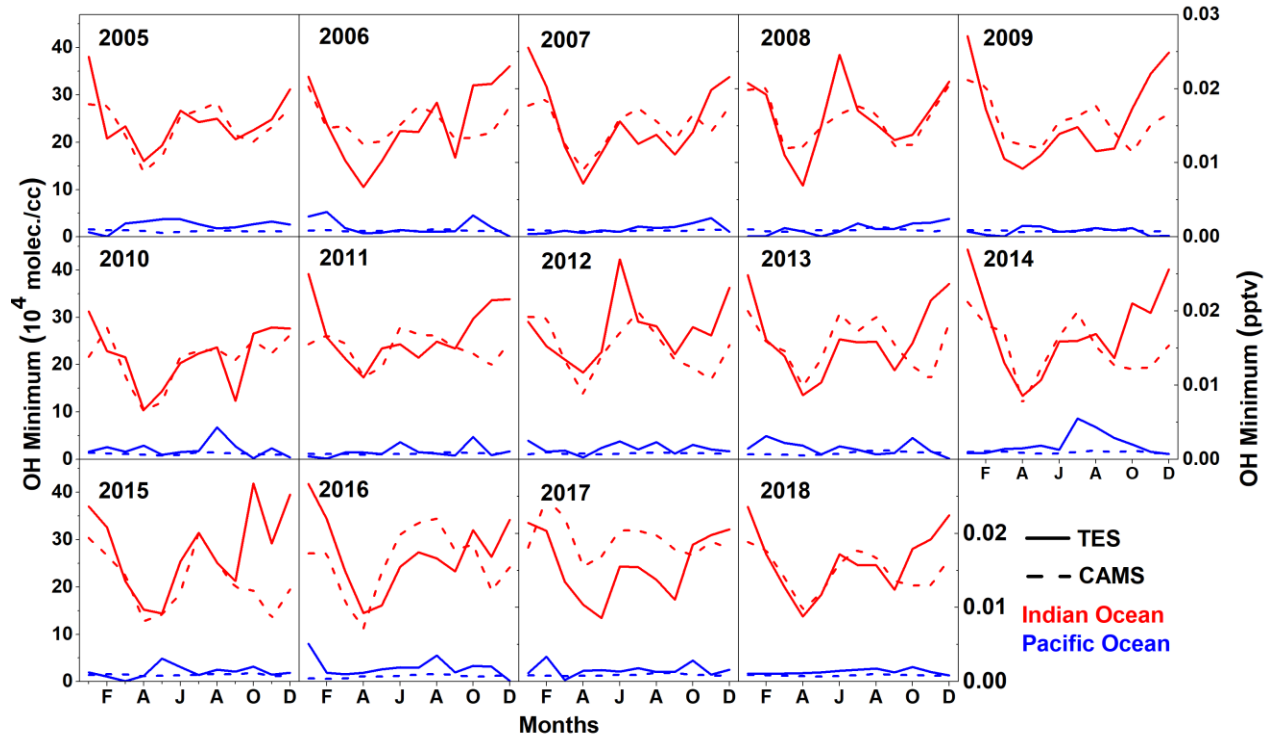
638 of surface OH in the selected region. The bottom panels show the concentrations of mean surface OH

639 estimated from the TES and CAMS reanalysis data (third panel from top), and different trace gases averaged

640 over the minimum region for the study period. All data are monthly averaged.

641





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643 Fig. 7. The OH minima at the surface of Pacific and Indian Oceans averaged for each month and year.

644 Alternate months are marked on the x-axis (e.g. February is F, April is A and December is D).

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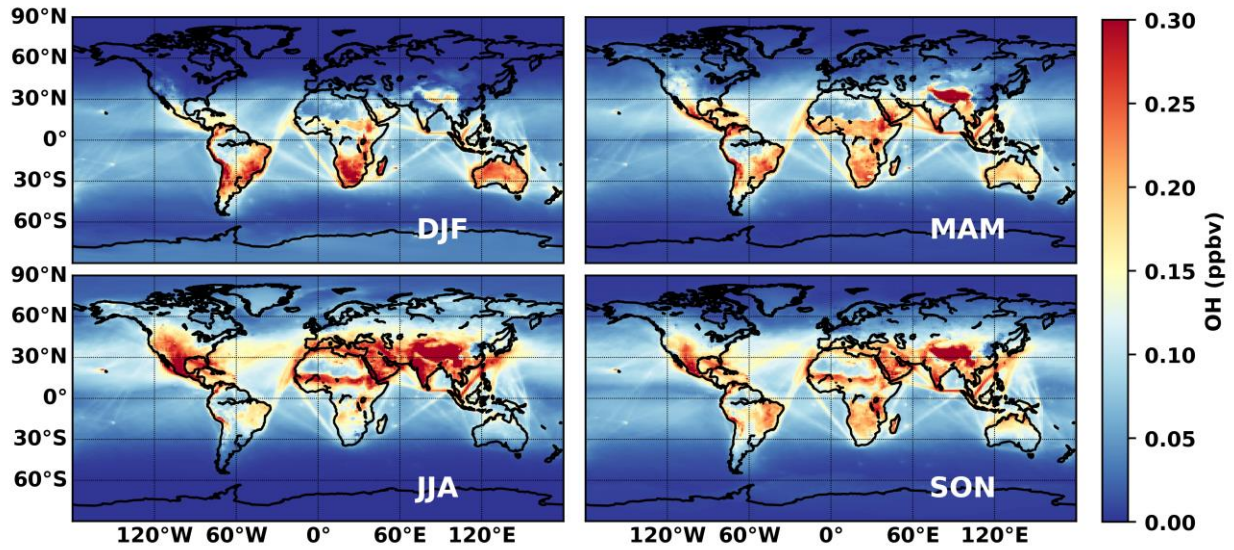
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656 Fig. 8. Surface OH values simulated by the WACCM model for different seasons of 2005. The seasons are  
 657 defined as winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

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