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Martyn P. Chipperfield, Andreas Chrysanthou, Robert P. Damadeo, Martin Dameris, Sandip S. Dhomse, Vitali E. Fioletov, Stacey M. Frith, Sophie Godin-Beekmann, Birgit Hassler, Jane J. Liu, et al.

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## I. INTRODUCTION

Lu (2022) (hereafter L2022) used the Trajectory-mapped Ozone-sonde dataset for the Stratosphere and Troposphere (TOST) to argue that there has been very substantial ozone depletion (>80%) in the tropical (30°S–30°N) lower stratosphere (LS) since the 1960s. This was labeled a “large and all-season ozone hole.” Here, we show that this claim is false due to erroneously large tropical ozone values in the interpolated sparse historical TOST data. In addition, L2022 repeats the suggestion made in a number of the author’s earlier papers that cosmic rays are involved in stratospheric ozone

depletion. This claim is also not valid; a huge body of work has explained the observed stratospheric ozone depletion through a well-established gas phase and heterogeneous chemistry following the emission of ozone-depleting substances (ODSs) through human activities.

We expand on these points below. In particular, we present a simple analysis of the TOST dataset used by L2022 and show its unsuitability for the application performed. In contrast, we then summarize the much smaller observed variations in ozone in the tropical LS based on many international efforts of data validation and quality assurance, which are not cited by L2022. We then

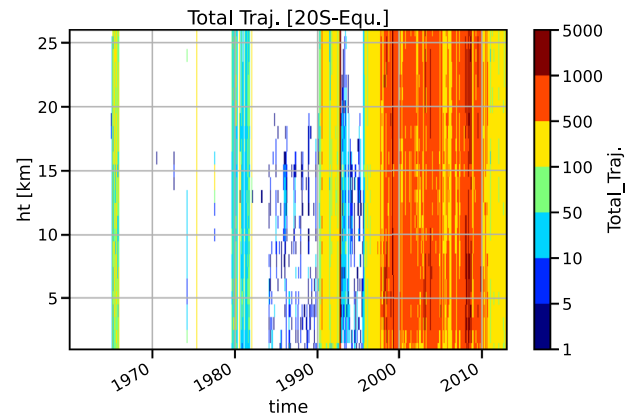
discuss flaws in the cosmic-ray electron-induced mechanism proposed by L2022 as being the main driver of stratospheric ozone losses.

## II. OZONE IN THE TROPICAL LOWER STRATOSPHERE

### A. TOST data used by L2022

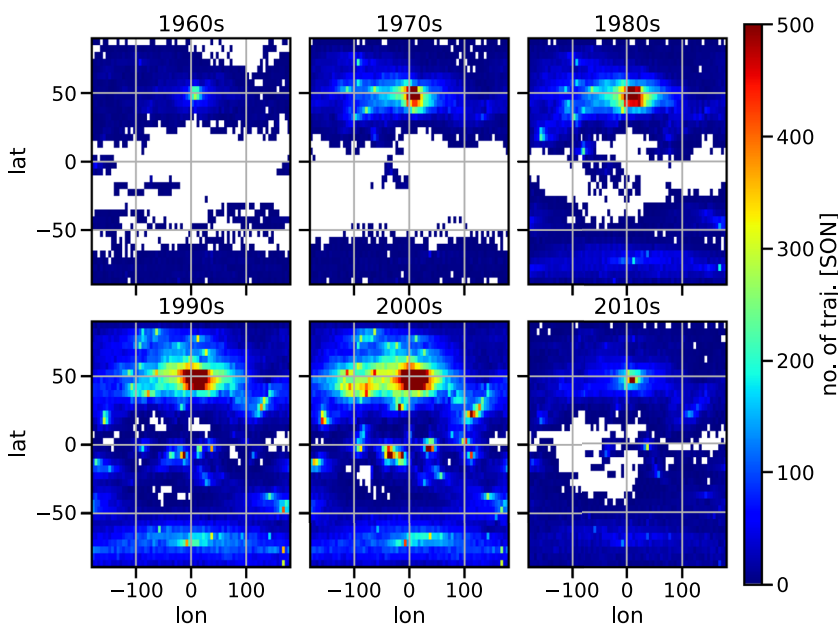
The World Ozone and Ultraviolet Radiation Data Center (WUOZC) website (<https://woucd.org/data.php>) hosts the TOST data in two formats: (1) ozonesonde data at 1 km intervals in altitude expanded with 4-day forward and backward trajectories to increase spatial sampling (hereafter labeled TOST\_RAW) and (2) a smoothed, gap-filled version of TOST\_RAW using linear interpolation of maps (hereafter labeled TOST\_SM). Methodologies used to construct these two datasets are described by Liu *et al.* (2013a; 2013b). In brief, profile data from about 50 000 ozonesonde profiles (1965–2012) are spatially extended using backward and forward trajectories from meteorological re-analyses to construct a global ozone climatology. Both TOST\_RAW and TOST\_SM datasets are provided in monthly, annual, and decadal means. L2022 does not specify which TOST dataset is used in that study, but we infer below (see Fig. 3 discussion) that it is TOST\_SM. Thus, the ozone depletion diagnosed by L2022 clearly depends entirely on the accuracy and representativeness of the smoothed, gap-filled TOST\_SM data in the tropics, especially in the 1960s–1980s.

Figures 1 and 2 show the coverage of the raw trajectory-extended ozonesonde data used to create the TOST datasets. The observed data coverage in the tropics is poor from the 1960s to the 1980s [see also Table I, Fig. 8 of the study by Liu *et al.* (2013a), and Figs. 1 and 12 of the study by Liu *et al.* (2013b)], which affects the validity of the data created by the TOST\_SM gap-filling algorithm. Moreover, in the southern tropics ( $20^{\circ}\text{S}$ – $0^{\circ}$ ), where L2022 diagnosed the largest ozone depletion, the only observations in



**FIG. 2.** Number of trajectory-extended ozonesonde observations (per km per month) in the TOST dataset in the latitude range  $20^{\circ}\text{S}$ – $0^{\circ}$ . Note the very sparse sampling in the 1960s (except 1965), 1970s, and 1980s.

the 1960s are in 1965, and the data coverage is very sparse until the late 1990s when a dedicated tropical ozonesonde network, SHADOZ (Southern Hemisphere Additional Ozonesondes), was initiated (Thompson *et al.*, 2003). While the lack of tropical ozonesonde observations is one severe limitation to diagnosing ozone changes in this region, the problem is further compounded by variable quality control and the instrument response at the different sonde stations between the 1960s and 1980s [e.g., at Pune in the 1980s—see the study by Rohtash *et al.* (2016)]. Reprocessing of most tropical ozonesonde data has greatly enhanced the quality of profiles (Thompson *et al.*, 2017; Sterling *et al.*, 2018), but those profiles were not used in TOST. The limitations imposed by sparse data and large data gaps are discussed in the TOST papers; for each altitude,



**FIG. 1.** Number of trajectory-extended ozonesonde observations in the TOST dataset for the September–October–November (SON) season as a function of longitude ( $^{\circ}\text{E}$ ) and latitude ( $^{\circ}\text{N}$ ) at a grid resolution of  $5^{\circ} \times 5^{\circ}$  for six different decades at 15 km. White indicates no observations. Note the lack of tropical observations in the 1960s–1980s, especially south of the equator. Sampling patterns for other seasons are similar.

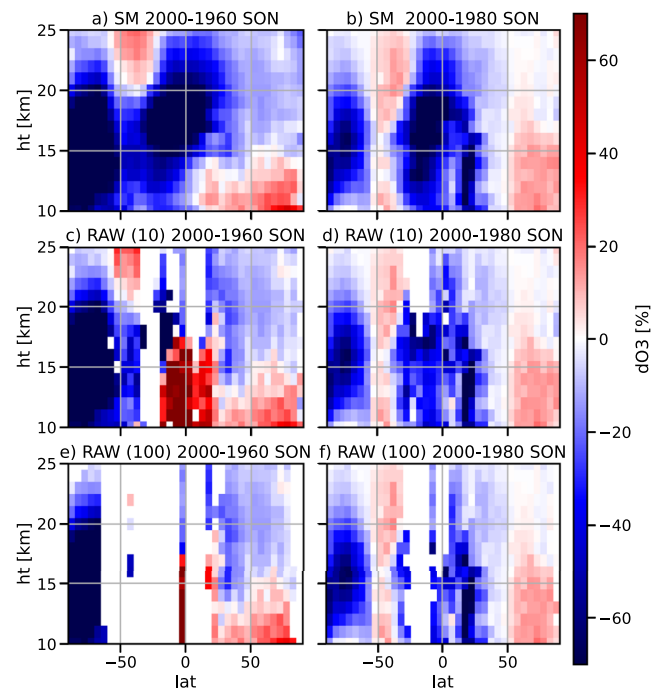
**TABLE I.** Number of ozonesonde profiles in the inner tropics ( $20^{\circ}\text{S}$ – $20^{\circ}\text{N}$ ) used in the study by Liu *et al.* (2013b) to construct TOST datasets for the 1960s and 1970s.

Station ID	Station name	Latitude ( $^{\circ}\text{N}$ )	Longitude ( $^{\circ}\text{E}$ )	Period of observation	Number of profiles
108	Canton Island	−2.8	−171.7	1965	31
109	Hilo	19.6	−155.1	1964–1965	17
149	La Paz	−16.5	−68	1965	10
187	Pune	18.5	73.8	1966–1976	135
205	Trivandrum	8.5	76.97	1969–1979	32
203	Ft. Sherman	9.3	−80	1977	16
206	Bombay	19.1	72.8	1968–1969	7
219	Natal	−5.8	−35.2	1979	7
224	Chilca	−12.5	−76.8	1975	3
225	Kourou	5.3	−52.7	1974	3
236	Coolidge Field	17.3	−61.8	1976	7

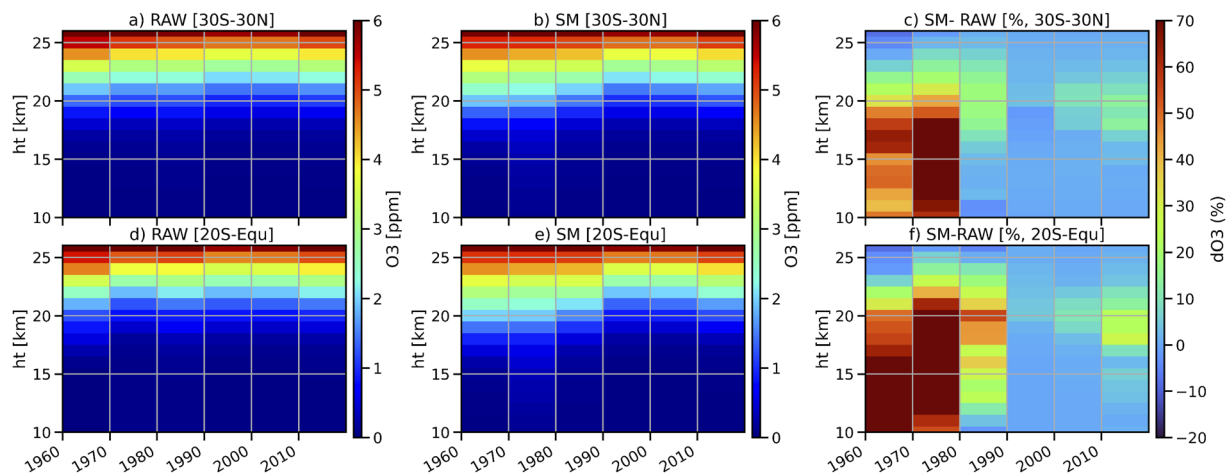
maps are provided, with the data showing the standard error and the number of observations entering each TOST\_RAW mean value. Using this information, the user can judge the quality of individual TOST\_RAW averages and filter as required for appropriately robust data.

Figure 3 shows the differences in the TOST\_SM and TOST\_RAW decadal means for the September–October–November (SON) season, both between 2000 and 1960 and between 2000 and 1980. In addition to the simple difference between the TOST\_SM decadal means [Figs. 3(a) and 3(b)], we also calculate decadal mean differences with the TOST\_RAW data but filtered to only include grid cells with a minimum number of data points in the calculation of the decadal mean: 10 [Figs. 3(c) and 3(d)] and 100 [Figs. 3(e) and 3(f)]. Comparison of our Fig. 3 with the corresponding SON panels in Figs. 1–3 of L2022 confirms that he analyzed the seasonal mean decadal mean smoothed, gap-filled TOST\_SM dataset [i.e., our Figs. 3(a) and 3(b)]. These data show an apparent large depletion of ozone in the TOST\_SM data of up to 80% since the 1960s at around 17.5 km altitude and in the latitude range  $20^{\circ}\text{S}$ – $0^{\circ}$ . However, this change in the smoothed, gap-filled TOST\_SM data is an artifact of the sparsely sampled tropical region, as noted above, and there is no robust link to the available observations. In Figs. 3(c)–3(f), the TOST\_RAW data do not show such a large ozone decline, and in Figs. 3(c) and 3(e), ozone even increases below 18 km.

The impact of smoothing on the sparse observations in TOST\_SM can be seen from the zonal mean climatology. Figure 4 compares decadal mean TOST data, as used by L2022, for both the wider tropics ( $30^{\circ}\text{S}$ – $30^{\circ}\text{N}$ ) and the  $20^{\circ}\text{S}$ – $0^{\circ}$  sub-region. The smoothing in TOST\_SM not only fills gaps but has also artificially increased the mean ozone values in the tropical lower stratosphere. In the absence of observations in the tropical region, ozone values are interpolated from higher latitudes where ozone concentrations are often higher than those in the tropics. This will lead to an erroneously large diagnosed ozone change. This source of bias is discussed in the first TOST paper (Tarasick *et al.*, 2010). Even small biases, if not addressed, can invalidate trend analyses. In the study by Liu *et al.* (2013b), some simple trend calculations



**FIG. 3.** Difference in decadal mean zonal mean ozone for the SON season from TOST datasets. (a) TOST\_SM 2000 minus 1960, (b) TOST\_SM 2000 minus 1980, (c) TOST\_RAW 2000 minus 1960 restricted to having at least ten trajectory points in each grid cell ( $1\text{ km} \times 5^{\circ}$  latitude) in the zonal mean decadal mean, (d) TOST\_RAW 2000 minus 1980 restricted to having at least ten TOST data points per grid cell, (e) TOST\_RAW 2000 minus 1960 restricted to having at least 100 TOST data points per grid cell, and (f) TOST\_RAW 2000 minus 1980 restricted to having at least 100 TOST data points. Panel (a) agrees well with the corresponding panels in Figs. 1 and 2 of the study by L2022. Panel (b) agrees well with the corresponding panel in Fig. 3 of the study by L2022.



**FIG. 4.** Seasonal mean (SON) decadal mean  $O_3$  volume mixing ratio (parts per million) from TOST datasets for (top row)  $30^{\circ}\text{S}$ – $30^{\circ}\text{N}$  and (bottom row)  $20^{\circ}\text{S}$ – $0^{\circ}$  and for (a) and (d) TOST\_RAW (using all datapoints without filtering), (b) and (e) smoothed, gap-filled TOST\_SM, and (c) and (f) percentage difference TOST\_SM minus TOST\_RAW. Note how the smoothing increases the ozone mixing ratio in these tropical averages during 1960–1980 compared to the raw data. Note that some decadal means, especially for  $20^{\circ}\text{S}$ – $0^{\circ}$  before the 1980s, are based on very few data points (see Figs. 1 and 2 and Table I).

are presented using the TOST\_RAW dataset and after careful filtering for adequate data density. These, unsurprisingly, agree well with trends calculated from satellite and ground-based total ozone measurements.

L2022 (his Fig. 5) showed that the TOST\_SM data strongly overestimate the independent data from GOZCARDS (Global Ozone Chemistry And Related trace gas Data records for the Stratosphere; Froidevaux *et al.*, 2015) and BDBP (Binary DataBase of Profiles; Hassler *et al.*, 2008) until after the 1990s (plotted as anomalies on different altitude levels). Given that both of these datasets have more data points contributing to the monthly zonal mean ozone in the 1980s and 1990s (from satellite data), this is further evidence of bias in the TOST\_SM data over the tropics for the 1990s, 1980s, and earlier.

## B. Observed changes in tropical ozone

In addition to the limitations of the L2022 TOST analysis described above, the results presented by that study are in strong contradiction with the very large amount of research performed over the last several decades. Changes and trends in both tropical total column ozone and vertically resolved tropical LS ozone have been shown and discussed in every Scientific Assessment of Ozone Depletion since the early 1990s (WMO, 1992). L2022 states that “no  $O_3$  hole over the tropics has been reported” and cites the most recent assessment (WMO, 2018). However, the reason for this is simple: even with the modified definition of an ozone “hole” as created by L2022 (i.e., a decrease in  $O_3$  by more than 25% relative to levels in the 1960s), there is no evidence for such a decrease in the tropical ( $20^{\circ}\text{S}$ – $20^{\circ}\text{N}$ ) lower stratosphere (100–70 hPa) from observational records. Measurements of ozone in the tropical lower stratosphere are derived from a multitude of ground- and space-based instruments. Although the number of long-term records in the tropics prior to 2000 is limited, particularly for vertically resolved profiles

covering the tropical upper troposphere-lower stratosphere (UTLS) where natural variability is comparatively large, the analyses of these data over the last few decades have painted a consistent picture of how ozone has changed in this region.

Total column measurements from both ground stations and satellites have routinely shown values that are mostly constant, aside from variability (e.g., due to interannual dynamical variations). Tropical trends, using data records starting as far back as the 1970s (Sahai *et al.*, 2000), were first reported as negative with a magnitude less than 2% per decade and having generally larger uncertainties than their determined trend (e.g., Stolarski *et al.*, 1991; WMO, 1992 and references therein). These analyses have been updated and refined over the years with similar results (e.g., Reinsel *et al.*, 1994; 2005; Harris *et al.*, 1997; Fioletov *et al.*, 2002; WMO, 2011; Chhade *et al.*, 2014; Weber *et al.*, 2018 and 2022). While total column ozone may not be the best metric by which changes in the tropical lowermost stratosphere could be assessed, it is a reliable metric for assessing potential changes in surface UV exposure. The total decrease in tropical total column ozone is only about 1% between the 1964–1980 and 2017–2020 averages (Weber *et al.*, 2022), meaning that harmful UV surface exposure remains mostly unchanged in the tropics until today, contrary to the concerns brought forth by L2022. This small change in total ozone is expected from positive trends in the tropical troposphere and negative trends in the tropical LS [see WMO (2018) and references therein].

Vertically resolved observations of the tropical UTLS prior to 2000 came from a limited number of ground-based (mostly ozonesondes) and satellite-based instruments. Trends in this region are difficult to determine because of the large natural variability that can complicate trend analyses (SPARC/IO3C/GAW, 2019 and references therein), the limited spatial coverage of ground stations with well-calibrated ozonesonde records, and the reduced vertical resolution and increased measurement uncertainty of satellite data

in the UTLS, depending on the measurement system (Hassler *et al.*, 2014). While there have been some variations in derived trends over the years (e.g., McCormick *et al.*, 1992; Wang *et al.*, 1996; 2002; and Randel and Thompson, 2011), more recent results that take advantage of longer records that have been largely consistent as refinements to past datasets have become increasingly minor, and analysis techniques have evolved (e.g., Harris *et al.*, 2015 and references therein; Steinbrecht *et al.*, 2017; Ball *et al.*, 2018; and SPARC/IO3C/GAW, 2019 and references therein). Although uncertainties are large, tropical lower stratospheric ozone trends derived from both sondes and satellites are negative, with a magnitude of roughly 3%–5% per decade for the period typically ranging from 1984 to 1997, and these trends remain negative thereafter, with a magnitude of roughly 2% per decade for the period 2000–2020 (Thompson *et al.*, 2021; Godin-Beekmann *et al.*, 2022). These values are significantly smaller than the trends that are suggested by Fig. 3 of L2022 (about –20% per decade). The limited amount of measurement data prior to 1980 precludes the evaluation of trends back to 1960, but chemistry–climate models have advanced to replicate the long-term changes seen by observations reasonably well. Figures 3–16 of WMO (2018) show both the observational and model data at 70 hPa/19 km in the tropics, and model simulations show an average total decrease in ozone at this level from 1970 to 2000 of ~6%, where Fig. 2 of L2022 suggests a total decrease of nearly 60%.

### III. MECHANISM OF OZONE LOSS

Independent of our assertion that there has not been large ozone depletion over the tropics (Sec. II), many aspects of stratospheric chemistry and dynamics presented by L2022 to explain this apparent depletion are incorrect and require some comment. L2022 did not consider any of the other mechanisms for ozone changes in the tropical UTLS that have been widely discussed in the ozone community (e.g., WMO, 2018; Dietmüller *et al.*, 2021). In particular, circulation changes [strengthening of the Brewer–Dobson circulation (BDC), i.e., increases in tropical upwelling and enhanced mixing between tropics and subtropics (Ball *et al.*, 2020)] related to increasing greenhouse gases (GHGs) are the main drivers of the small ozone decreases in this region (e.g., Eyring *et al.*, 2010; Dhomse *et al.*, 2018; and Dietmüller *et al.*, 2021). It is worth noting that recent analyses of observations support such an explanation for tropical lower stratospheric ozone loss. When a coordinate transformation is performed to look at trends relative to the tropopause height for either ground- (Thompson *et al.*, 2021) or space-based (Bognar *et al.*, 2022) observations, the negative trends just above the tropopause largely disappear, showing how dynamically driven trends in the tropopause region (Pisoft *et al.*, 2021) are primarily responsible for these ozone trends.

#### A. CRE model

The cosmic-ray-driven electron-induced (CRE) mechanism is not the cause of stratospheric ozone depletion in the polar regions or elsewhere. This mechanism has been thoroughly rebutted in previous comments on the author's papers (e.g., Harris *et al.*, 2002; Patra and Santhanam, 2002; Müller, 2003; Müller and Grooß, 2009 and 2014; Grooß and Müller, 2011 and 2013; and Nuccitelli *et al.*, 2014).

L2022 correlates ozone time series with a proxy representing cosmic-ray-driven ozone losses (“CRE model”), through his Figs. 6(a) and 6(b). The CRE model proxy time series is not clearly distinguishable from the superposition of ODS (ozone-depleting substance) changes [given by effective equivalent stratospheric chlorine (EESC)] and solar irradiance changes (solar activity). Figure 5(a) shows the CRE model proxy from the study by L2022 (digitized from his figure) along with the best fit of the EESC and Mg II UV solar irradiance activity index. The correlation of the SH polar CRE model proxy with the combined polar EESC and solar proxy is 0.96. The correlation is lower (0.74) in the tropical region.

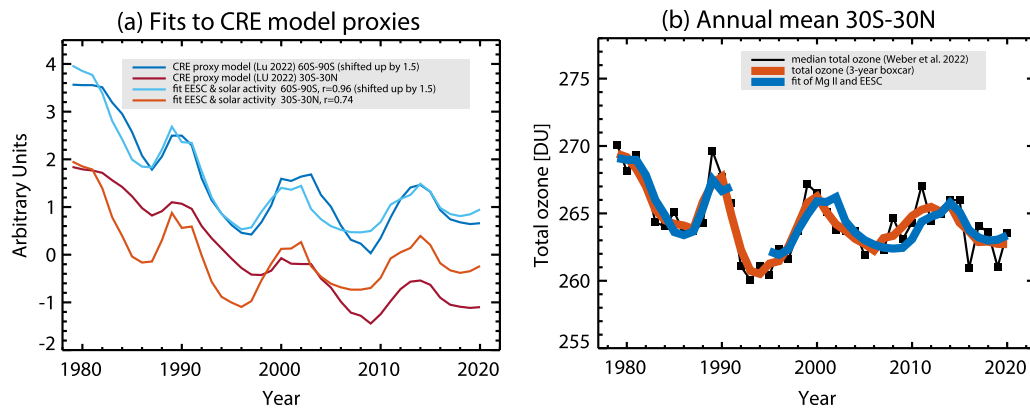
Both EESC and solar activity are well-known drivers of ozone changes (e.g., WMO, 2018). It is known that the cosmic ray flux is modulated by solar activity, meaning that strong solar winds during solar maximum activity shield the earth from cosmic rays such that the cosmic ray flux is anticorrelated with solar flux variations (e.g., Usoskin *et al.*, 2005). This means that the decadal variation in total ozone can be explained by solar irradiance variation. The solar radiative effect on total ozone is well-established and in agreement with model simulations (e.g., Labitzke and van Loon, 1988; Maycock *et al.*, 2018; and Dhomse *et al.*, 2022).

Figures 6(a) and 6(b) in the study by L2022 used total ozone data from different sources (Total Ozone Mapping Spectrometer, Ozone Monitoring Instrument, and Ozone Mapping and Profiler Suite) without removing potential biases and drifts between the datasets, a step that is essential for accurate diagnosis of trends. Figure 5(b) shows the tropical total ozone time series, which is a median of five merged long-term total ozone datasets from the study by Weber *et al.* (2022). The median total ozone is considerably lower in the 1980s than what is shown in Fig. 6(b) of the study by L2022. The combination of EESC and the Mg II index can be reasonably fitted to the median total ozone, and additional factors such as the CRE mechanism are not needed to explain the variability in tropical total ozone. Some additional variability in tropical ozone is related to volcanic eruptions (Agung in 1963; El Chichón in 1982; and Mt. Pinatubo in 1991) that lead to stratospheric ozone depletion in the tropics due to heating and heterogeneous reactions on aerosol particles (e.g., Schoeberl *et al.*, 1993; Kilian *et al.*, 2020). These volcanic influences also coincided with the maximum phases in the solar cycle. Statistical analyses of ozone trends have found aliasing of the solar cycle and volcanic impacts (Chiodo *et al.*, 2014; Damadeo *et al.*, 2014; Dhomse *et al.*, 2016; and Kuchar *et al.*, 2017), and therefore, attribution of ozone trends has to be performed carefully.

For the above-mentioned reasons, a simple correlation of ozone with the CRE model proxy cannot be used as any proof of the cosmic-ray-driven electron-induced (CRE) mechanism.

#### B. Observations of CFC-12 and the tropopause

To support the explanation of chemical tropical ozone depletion via the CRE mechanism, L2022 used measurements of CFC-12 [his Fig. 4(d)] from the Cryogenic Limb Array Etalon Spectrometer (CLAES, incorrectly referred to as CLEAS throughout L2022) onboard the Upper Atmosphere Research Satellite (UARS). L2022 states that “the CFC-12 concentration was depleted in the lower stratosphere below 25 km over the tropics (at latitudes 30°S–30°N),



**FIG. 5.** (a) Normalized CRE model proxy, digitized from Figs. 6(a) and 6(b) in the study by L2022, in the tropics and SH polar region along with the best fits of EESC and solar UV activity proxy (Mg II index). EESC is obtained from the NASA automailer ([https://acd-ext.gsfc.nasa.gov/Data\\_services/automailer/index.html](https://acd-ext.gsfc.nasa.gov/Data_services/automailer/index.html)) and assumes a mean age-of-air of 5.5 years and a width of 2.75 years in the polar region and 3.5 and 1.5 years outside the polar regions, e.g., tropics. The Mg II index is obtained from <https://www.iup.uni-bremen.de/UVSAT/Datasets/mgii>. (b) Median total ozone time series from five merged total ozone datasets (Weber et al., 2022) and the best fit of EESC and solar activity proxy (Mg II index). Due to the major impact of the Mt. Pinatubo volcanic eruption in 1991, the period 1991–1994 was excluded from the fit.

most significant in the zone at 16–20 km and at 20°S–20°N, in which correspondingly the circularly symmetric annual mean tropical  $O_3$  hole is centrally located.” This statement is wrong on two counts. First, the tropical tropopause is located at about 17–18 km (e.g., Hoffmann and Spang, 2022), so measurements below the tropopause (i.e., in the troposphere) are not relevant for the stratospheric CRE mechanism. Above 18 km, in the inner tropics (10°S–10°N), CFC-12 is rather constant [about 472 ppt, L2022 Fig. 4(d)], as expected based on its atmospheric lifetime of many decades in this region (Chipperfield et al., 2014). Lower values of CFC-12 toward the mid-latitudes are caused by in-mixing of mid-latitude air into the tropics (e.g., Butchart et al., 2010; Abalos et al., 2015 and 2021; Ploeger et al., 2021; and Poshyvailo-Strube et al., 2022). Second, the CRE mechanism is based on the destruction of CFC-12 (and other species) on atmospheric cloud particles by dissociative electron attachment (DEA) (L2022; Lu and Sanche, 2001). According to the CRE mechanism, the lifetime of CFC-12 in the presence of particles is hours (Lu and Sanche, 2001; Müller, 2003), so the action of the CRE mechanism in the tropics should lead to (patchy) areas with very low CFC-12 presence in association with clouds. Such low presence of CFC-12 in the tropical lower stratosphere is not obvious in either Fig. 4(d) of the study by L2022 or in any other CFC-12 measurement datasets that we are aware of (e.g., Tegtmeier et al., 2016).

L2022 also states that “significant decompositions of CFCs and  $N_2O$  but not  $CH_4$  occur in the lower Antarctic stratosphere during winter.” This statement is in contradiction with the observation that  $N_2O$  and  $CH_4$  are well correlated throughout the stratosphere, consistent with a similar (photochemical) loss mechanism for both species in the stratosphere (e.g., Michelsen et al., 1998). Mixing ratios of  $N_2O$  are indeed particularly low in the polar regions (especially in winter), which is an effect caused by transport through the Brewer–Dobson circulation (BDC) and the descent of stratospheric air in polar regions. This polar descent is obvious in measurements of both  $N_2O$  and  $CH_4$  (e.g., Müller et al., 1999; Ray et al., 2002; and Strahan et al., 2015).

### C. Stratospheric circulation

L2022 repeats a statement made similarly in previous papers by the author (e.g., Lu, 2013), namely, “the transport lag times of CFCs from the troposphere to the lower stratosphere over the Antarctic and the tropics, [...] are about 1 year and 10 years, respectively.” This issue has already been debated and shown to be flawed (Müller and Groöf, 2014 and references therein). The erroneous information repeated by L2022 is in contrast to many observations and the theoretical understanding that the stratospheric BDC constitutes young air entering the stratosphere in the tropics. The stratospheric air is transported upward in the (leaky) tropical pipe (e.g., Neu and Plumb, 1999; Butchart, 2014) and then poleward in the lower and upper branches of the BDC, leading to the largest mean ages (of the order of four years) in the polar regions (e.g., Bönisch et al., 2011; Ploeger et al., 2021; and Poshyvailo-Strube et al., 2022). These misconceptions of L2022 might contribute to his incorrect interpretation of tropical lower stratospheric chlorine and ozone chemistry. A full summary and explanations of the atmospheric processes responsible are provided in the scientific ozone assessments (WMO, 2014, Chap. 2; WMO, 2018, Chap. 3).

### D. Tropical stratospheric clouds (TSCs)

The stratospheric CRE mechanism relies on the presence of particles in the stratosphere, referred to as TSCs by L2022. However, there is little observational evidence for clouds in the tropical lower stratosphere; while temperatures there are low, the abundance of condensable material (in particular water vapor) is also very low (e.g., Brewer, 1949; Lu et al., 2020). Thus, ice clouds are not frequently observed in the tropics. Peter et al. (2003) observed subvisible, large-scale cirrus clouds, referred to as Ultrathin Tropical Tropopause Clouds (UTTCs), a few hundred meters below the tropical cold point tropopause. Zou et al. (2022) report that observations indicate the occurrence of ice clouds with cloud-top heights of only 250 m above the first lapse rate tropopause in the tropics. Therefore, any processes related to a tropical CRE mechanism (which is



assumed by L2022 to be relevant for altitudes in the tropical stratosphere up to 25 km) could only occur infrequently and close to the tropopause because of the lack of particle surface area density in the tropical lower stratosphere.

#### IV. SUMMARY

As discussed above, and supported by extensive literature, there is no robust, credible observational evidence for substantial ozone depletion (i.e., an “ozone hole”) in the tropics. It is well known that climatological total ozone in the tropics is much lower than that in the mid-latitudes (e.g., [Sahai et al., 2000](#); [Weber et al., 2022](#)). Satellite and ozonesonde measurements indicate a 3%–5% per decade decline of tropical lower stratosphere ozone prior to 2000, far smaller than that reported by L2022. The stronger decline reported by L2022 is caused by inappropriate use of the gap-filled version of the TOST ozone dataset, which is based on sparse tropical ozone sondes before the 1990s. This misuse of data (TOST and total column ozone) shows the importance of collaboratively engaging with groups who obtain the measurements and create climatological datasets before performing such analyses.

Furthermore, the study by L2022 has multiple flaws in its discussion of atmospheric chemistry and dynamics, particularly in the proposed, and previously refuted (see Sec. III A), cosmic-ray-driven electron induced (CRE) mechanism. Evidence for the occurrence of tropical stratospheric clouds, as needed for the tropical CRE mechanism, is lacking, nor do CFC-12 observations show signatures of depletion in the tropical lower stratosphere, which could be associated with dissociative electron attachment-induced loss of CFC-12 on particulate matter (i.e., the CRE mechanism). Finally, it is worth reiterating that the CRE mechanism is also not responsible for polar LS ozone depletion. Polar ozone loss can be well explained by the gas phase and heterogeneous chemistry, based on extensive observations and modeling studies documented in many thousands of scientific papers on the topic [e.g., see [WMO \(2018\)](#) and references therein], which is not acknowledged by L2022.

L2022’s research paper is a severely flawed one. There is no tropical ozone hole, and the CRE mechanism does not explain observed changes in stratospheric ozone either in the polar regions or in the tropics.

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#### AUTHOR DECLARATIONS

##### Conflict of Interest

The authors have no conflicts to disclose.

#### Author Contributions

All authors contributed to writing this document.

**Martyn P. Chipperfield:** Conceptualization (lead); Writing – original draft (equal); Writing – review & editing (equal). **Andreas Chrysanthou:** Writing – original draft (equal); Writing – review & editing (equal). **Robert Damadeo:** Writing – original draft (equal); Writing – review & editing (equal). **Martin Dameris:** Writing – original draft (equal); Writing – review & editing (equal). **Sandip S. Dhomse:** Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Vitali Fioletov:** Writing – original draft (equal); Writing – review & editing (equal). **Stacey M. Frith:** Writing – original draft (equal); Writing – review & editing (equal). **Sophie Godin-Beekmann:** Writing – original draft (equal); Writing – review & editing (equal). **Birgit Hassler:** Writing – original draft (equal); Writing – review & editing (equal). **Jane Liu:** Writing – original draft (equal); Writing – review & editing (equal). **Rolf Müller:** Writing – original draft (equal); Writing – review & editing (equal). **Irina Petropavlovskikh:** Writing – original draft (equal); Writing – review & editing (equal). **Michelle L. Santee:** Writing – original draft (equal); Writing – review & editing (equal). **Ryan M. Stauffer:** Writing – original draft (equal); Writing – review & editing (equal). **David Tarasick:** Writing – original draft (equal); Writing – review & editing (equal). **Anne M. Thompson:** Writing – original draft (equal); Writing – review & editing (equal). **Mark Weber:** Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Paul J. Young:** Writing – original draft (equal); Writing – review & editing (equal).

#### DATA AVAILABILITY

The TOST data were obtained from <https://woudc.org/archive/products/ozone/vertical-ozone-profile/ozonesonde/1.0/tost/> (date of last access: August 16, 2022).

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