BAMS Article

The Imminent Data Desert: The Future of Stratospheric Monitoring in a Rapidly Changing World

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ABSTRACT: The Atmospheric Chemistry Experiment–Fourier Transform Spectrometer (ACE-FTS) on *SCISAT-1* and Microwave Limb Sounder (MLS) on NASA's *Aura* satellite have contributed significantly to understanding the impacts of human activities on the stratospheric ozone layer. The two-decade-long data record from these instruments has allowed quantification of ozone depletion caused by human-released ozone-depleting substances, the effects of extreme natural events like major volcanic eruptions including Hunga in 2022, and events amplified by human-caused climate change such as wildfires that inject material into the stratosphere, as happened over Australia in early 2020. The *Aura* platform is nearing the end of its operational lifetime, and *SCISAT-1* is over 20 years old. Their decommissioning will cause a substantial gap in the measurement of critical atmospheric components, including water vapor, inorganic chlorine species, and tracers of stratospheric transport. This upcoming "data desert" poses significant challenges for monitoring the recovery of the ozone layer and assessing the effects on stratospheric composition of future extreme events, threats posed by increases in space debris from satellite burn-up, and the possible injection of stratospheric aerosol to mitigate global warming. The lack of confirmed future missions that can provide daily near-global profile measurements of stratospheric composition highlights the need for observational strategies to bridge this impending gap. This paper discusses the essential role of ACE-FTS and MLS in advancing our understanding of the stratosphere, the impact of data loss after the cessation of one or both instruments, and the urgency of developing strategies for mitigating the impact of these observational losses at a time marked by dramatic changes in the stratosphere due to human and natural factors.

SIGNIFICANCE STATEMENT: We highlight the critical role that data from the ACE-FTS and Microwave Limb Sounder (MLS) satellite instruments have played in advancing our understanding of stratospheric composition and the impacts of human activities on the ozone layer. As these instruments near the end of their operational lifetimes, the imminent loss of data, particularly of stratospheric water vapor, chlorine species, and tracers of transport, portends profound and irrevocable gaps in atmospheric observations. This loss of observational capability will occur at a time of rapid climate change and hinder our understanding of the stratosphere's response to, and its coupled role in, continued climate forcing. This paper emphasizes the urgency of addressing this data desert, highlighting the need for sustained, coordinated, global measurement capabilities for these crucial constituents.

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1. Introduction

Earth's stratospheric ozone layer protects humans, animals, agriculture, and ecosystems against the harmful effects of solar ultraviolet radiation (Madronich et al. 1998; Bais et al. 2018). Variations in stratospheric water vapor play an important role in climate change (Solomon et al. 2010; Dessler et al. 2013). Since their respective launches in 2003 and 2004, data from the Atmospheric Chemistry Experiment–Fourier Transform Spectrometer (ACE-FTS) instrument on the Canadian Space Agency *SCISAT-1* satellite (Bernath et al. 2005) and the Microwave Limb Sounder (MLS) instrument on the NASA *Aura* satellite (Waters et al. 2006) have been essential to the global atmospheric science community's efforts to quantify the impacts of human activity and extraordinary natural events on Earth's ozone layer and stratospheric composition and chemistry more broadly. Measurements acquired by ACE-FTS and MLS have enabled quantification of how the ozone layer has been altered by the human release of chlorofluorocarbons (CFCs) and other ozone-depleting substances (ODSs) regulated by the Montreal Protocol (Mahieu et al. 2014; Liveseyet al. 2015; Bernath and Fernando 2018), by natural factors such as the eruption of the undersea volcano Hunga in 2022 (Millán et al. 2022; Xu et al. 2022; Santee et al. 2023; Wilmouth et al. 2023), by extreme events such as the Australian wildfires of late 2019 and early 2020 (Schwartz et al. 2020; Santee et al. 2022; Strahan et al. 2022; Solomon et al. 2023), and during winter–spring periods with long-lasting cold conditions in the Arctic stratosphere that lead to severe ozone depletion (Manney et al. 2011, 2020; Griffin et al. 2019; Lawrence et al. 2020; Wohltmann et al. 2020; Feng et al. 2021; Grooß and Müller 2021). Furthermore, data from these satellite instruments have been instrumental in quantifying how long-term changes in stratospheric water vapor impact surface climate (Solomon et al. 2010; Banerjee et al. 2019; Tao et al. 2023) and for diagnosing changes in the strength of the Brewer–Dobson circulation (BDC), which alters the latitudinal distribution of stratospheric ozone (Strahan et al. 2020; Minganti et al. 2022; Prather et al. 2023).

Aura will be decommissioned no later than the middle of 2026, and *SCISAT-1* is 18 years beyond its design lifetime. While there will remain considerable capability to measure stratospheric profiles of ozone (O_3) and aerosols after these two missions end, the history of ozone research demonstrates that understanding changes in the ozone layer requires measurements of other species. There are no currently confirmed future spaceborne missions to measure, for example, the abundances of inorganic chlorine and nitrogen species such as chlorine monoxide (ClO), chlorine nitrate ($ClONO_2$), hydrochloric acid (HCl), and nitric acid (HNO_3) that are essential for relating the emissions of ODSs at Earth's surface to

changes in the thickness of the ozone layer (WMO 2022). Future daily near-global profile measurements of stratospheric water (H_2O) as well as tracers of stratospheric transport such as nitrous oxide (N_2O) or methane (CH_4) will be important for diagnosing changes in the strength of the BDC (Strahan et al. 2020; Minganti et al. 2022; Prather et al. 2023), but they also face an uncertain future. The current scientific consensus is that an increase in the BDC with global warming should lead to an accelerated recovery of total column ozone (TCO) at midlatitudes of both hemispheres, as well as a permanent reduction in TCO in the tropics that will result in increased exposure at the surface to harmful solar ultraviolet radiation (Butchart et al. 2006, 2011; Garcia and Randel 2008; Abalos et al. 2021). Finally, climate models (Smalley et al. 2017; Keeble et al. 2021) and theory (Hu and Vallis 2019) predict a future rise in stratospheric H_2O due to increases in the temperature of the tropical tropopause associated with global warming. Should the future abundance of stratospheric H_2O rise appreciably relative to present-day levels, declines in TCO would likely occur in both midlatitudes (Dvortsov and Solomon 2001; Anderson and Clapp 2018) and northern polar regions (Kirk-Davidoff et al. 1999; von der Gathen et al. 2021). Finally, stratospheric ozone and water vapor are both greenhouse gases important for climate change, and accurate quantification of future climate change is a coupled chemistry–climate problem (IPCC 2021).

This article provides an overview of current and potential future stratospheric composition measurement capabilities. The discussion is organized in terms of H_2O, halogens (e.g., ClO, $ClONO_2$, and HCl), tracers of stratospheric transport (N_2O and CH_4), and anthropogenic pollution [e.g., hydrogen cyanide (HCN), carbon monoxide (CO), and methyl chloride (CH_3Cl)], ozone, and aerosol loading. We highlight the loss of data coverage that will occur, particularly for H_2O as well as halogens and tracers, once observations from MLS and ACE-FTS are no longer available—a time we term the "imminent data desert for stratospheric composition." We follow by providing numerous examples attesting to the importance of measurements from ACE-FTS and MLS for our current understanding of how human activity and extreme natural events have affected the ozone layer, both to document the vital role data from each platform have played and to highlight the observational capability that will be lost once data from these instruments no longer exist. Although we focus here on halogens, we note that spaceborne instruments also provide observations of many other species important for stratospheric ozone depletion, such as nitrogen oxides that are supplied to the stratosphere by the decomposition of N_2O. Finally, we conclude by noting the irony that the world's observational capability for diagnosing how the ozone layer is being altered by human and natural factors will diminish at the same time that mitigation of climate change by stratospheric aerosol injection—which poses a risk to the future recovery of stratospheric ozone—is the subject of increasing research and dialog [National Academy of Sciences (NAS) 2015, 2021; Haywood et al. 2022; Bednarz et al. 2023a; Tilmes et al. 2024].

2. Present and future measurement capabilities

Figure 1 shows a timeline of spaceborne observational capability for the profiling of stratospheric constituents by limb and occultation sounders over the past few decades, as well as the planned capability provided by currently confirmed future missions. The thickness of the bars represents the spatial density of observations, which is dependent upon observational technique, as shown schematically in Fig. 2. Solar occultation instruments typically provide slightly finer vertical resolution and better single-sounding precision than limb instruments, at the expense of much sparser spatial coverage. Ozone and aerosol observations from the Ozone Mapping and Profiler Suite–Limb Profiler (OMPS-LP) series of limb scattering instruments (Jaross et al. 2014; Loughman et al. 2018) and the Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS) (Wang et al. 2020) should

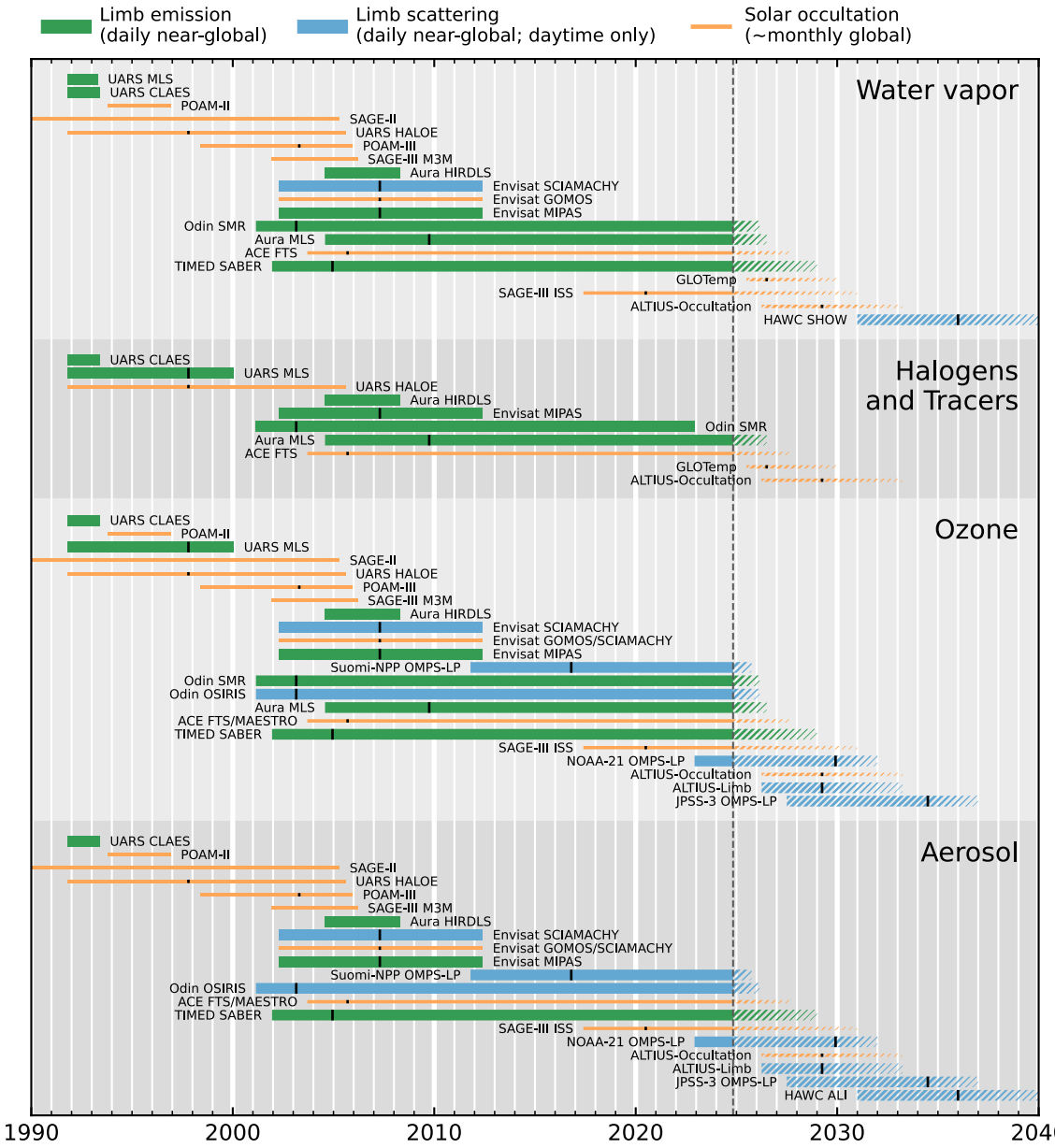

FIG. 1. Spaceborne limb or solar occultation observations of water vapor, halogens and tracers, O_3, and aerosol loading from 1990 to the present, as well as projected future measurements considering currently confirmed missions. Colors denote observational technique, whereas line thickness qualitatively represents the observational density (see Fig. 2). The thin black lines represent the end date of the design lifetime of the missions. The hashing represents the uncertainty in end dates of current satellite missions as well as uncertainty in future launch dates, and the vertical dashed line represents the present time at paper submission.

provide continuity into the future. In contrast, future measurements of stratospheric H_2O will be limited. SAGE III/ISS provides high-vertical-resolution measurements of the volume mixing ratio (VMR) of stratospheric water vapor (Davis et al. 2021). However, SAGE III/ISS measurements are geographically and temporally limited, and the continuation of instruments on the International Space Station beyond 2030 is uncertain. The planned NASA/Naval Research Laboratory Gas Filter Correlation Radiometer for Limb Occultation demo for upper atmosphere Temperature (GLOTemp) and ESA Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS) missions will use the solar occultation technique, similar to SAGE III/ISS but in a different orbit, again yielding sampling that is much sparser than is currently achievable by limb emission and limb scattering instruments (Fig. 2). The situation for observations of stratospheric water vapor should improve significantly with the launch of

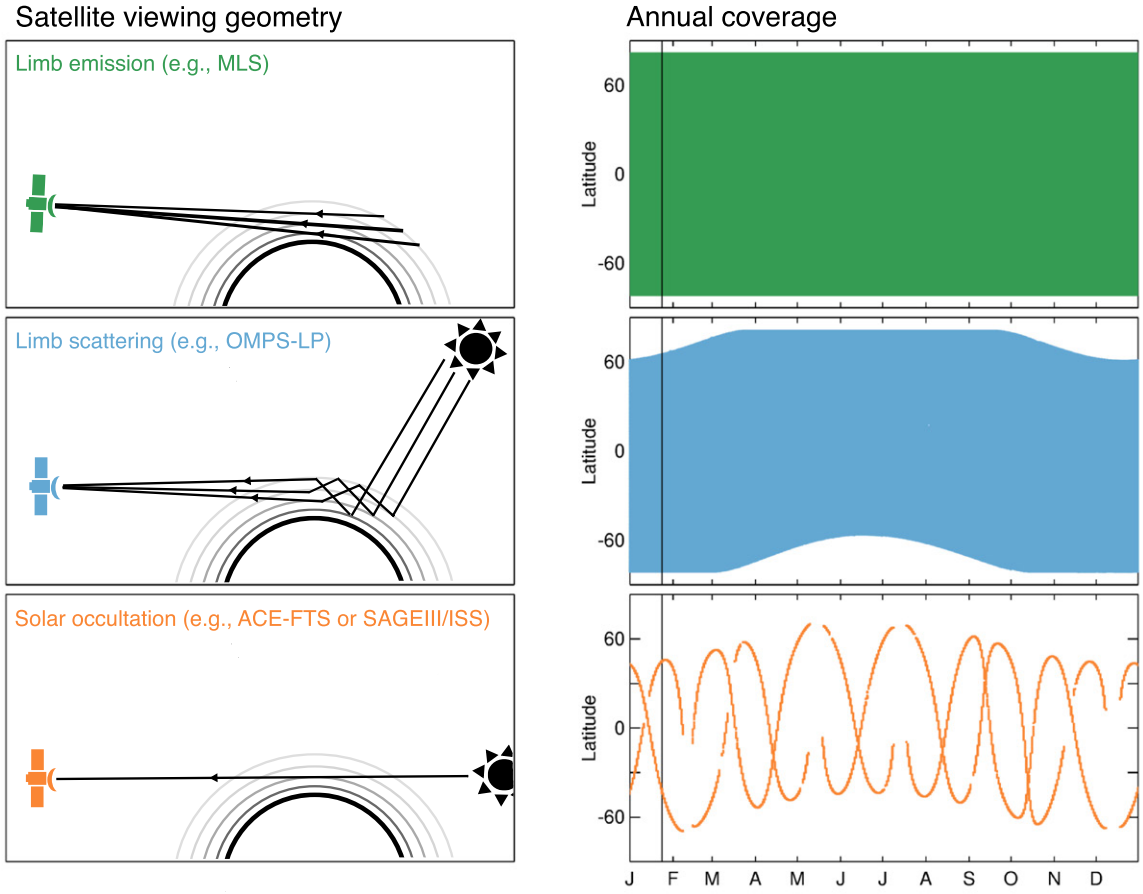

Fig. 2. (left) Satellite viewing geometry and consequent annual coverage for measurements obtained using either limb emission, limb scattering, or solar occultation. (right) The density of annual coverage from MLS on *Aura*, the OMPS-LP, and the SAGE III/ISS.

the Canadian High Spectral Resolution Lidar for Aerosols, Winds, and Clouds (HAWC) mission in 2030, 4–5 years after the end of the MLS record. Finally, there are presently no confirmed plans to obtain daily near-global coverage of halogenated species (e.g., ClO, $ClONO_2$, and HCl), tracers of stratospheric transport (e.g., N_2O and CH_4), or anthropogenic pollution (e.g., HCN, CO, and CH_3Cl), all of which are essential ingredients for quantifying the impact on the ozone layer of ODSs and other pollutants.

The left-hand side of Fig. 3 illustrates the present observational capability for stratospheric constituents afforded by the current fleet of instruments, and the right-hand side shows the measurement coverage that will exist in the future. The top row depicts Arctic polar views for a typical boreal winter day in mid-January, the middle three rows highlight global coverage for a typical boreal spring day in mid-April, and the bottom row depicts Antarctic polar views for a typical austral winter day in mid-July. The current fleet provides dense coverage of H_2O, halogens, transport and pollution tracers, and ozone over the tropical and midlatitude regions of the globe as well as throughout the Arctic and Antarctic. After the cessation of MLS and ACE-FTS observations, there will be limited coverage of the Arctic stratosphere during early boreal winter; similar gaps will exist over the Antarctic during the incipient phase of the annually occurring ozone hole in austral winter. The space-based observational system will continue to be supplemented by data from suborbital instruments as shown in Fig. 3. These include balloons carrying ozonesondes and frostpoint hygrometers (Thompson et al. 2004; Hurst et al. 2011; Stauffer et al. 2022), ozone and aerosol lidars (Leblanc and McDermid 2000; Chouza et al. 2020; Steinbrecht et al. 2023), and the Network for the Detection of Atmospheric Composition and Change (NDACC) sites (De Mazière et al. 2018) with Fourier transform infrared (FTIR) spectrometers that measure the total column

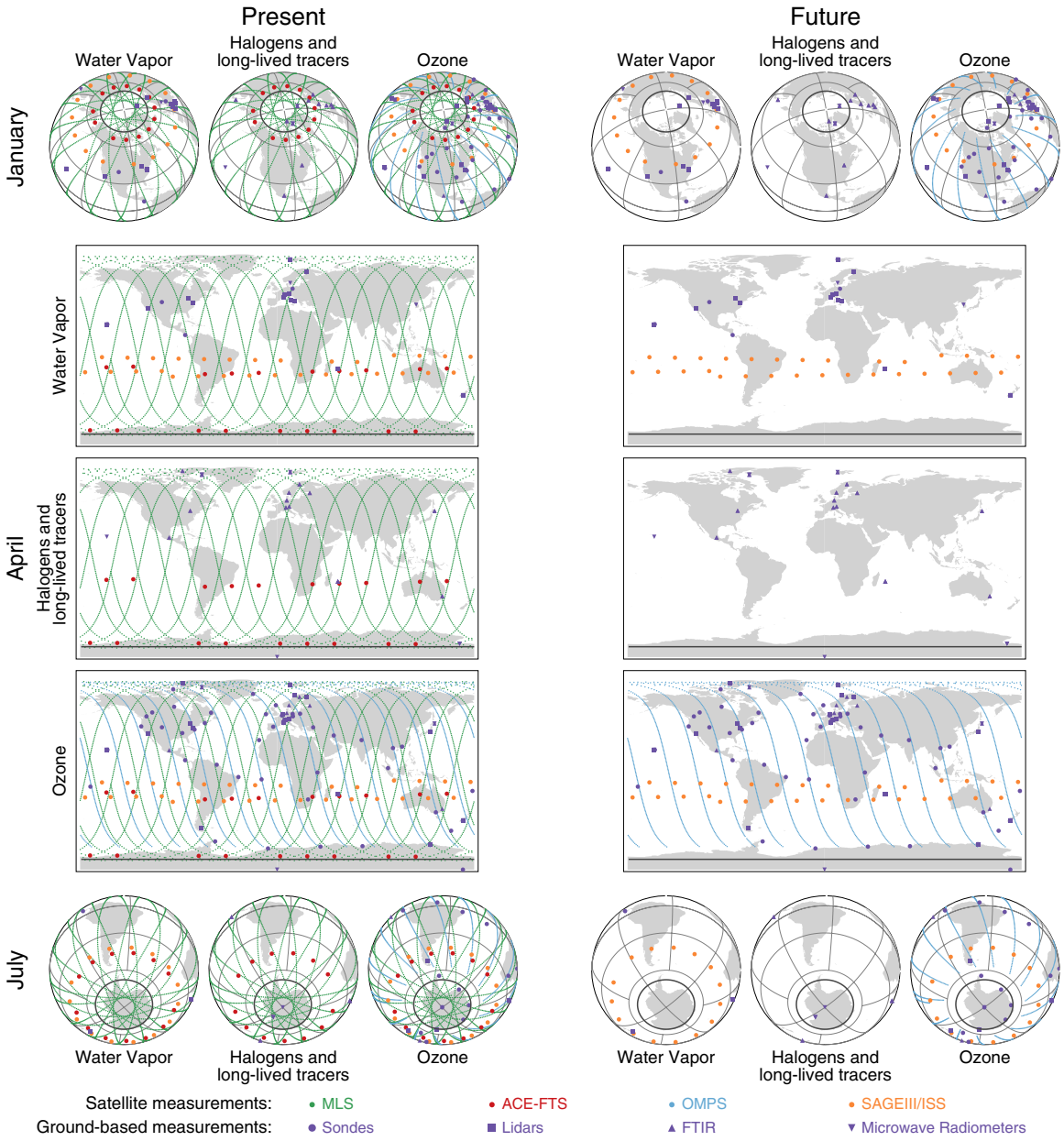

Fig. 3. Observational density of vertically resolved measurements of stratospheric water vapor, halogens and tracers, and O_3 (left) at present and (right) in the future once MLS and ACE-FTS are no longer able to provide observations. Symbols correspond to various satellite- and ground-based sensors (see legend); the black lines demarcate the boundary of polar night for the Arctic and Antarctic. For illustrative purposes, maps are shown for representative days in mid-January, mid-April, and mid-July for the Arctic, Mercator, and Antarctic projection maps, respectively. These dates are chosen to highlight how well the current fleet of spaceborne sensors, particularly MLS, can define initial conditions in the (top) Arctic and (bottom) Antarctic vortices in midwinter, a time when chemical loss of O_3, which requires sunlight, has typically not commenced to a substantial degree in most of the vortex. (middle) The stark contrast between the current dense sampling capability and the sparse future measurement capability for a typical boreal spring day.

abundance of a suite of gases including many halogens (Mahieu et al. 2014; Prignon et al. 2021) and tracers of stratospheric transport (Ostler et al. 2016; Minganti et al. 2022) and microwave radiometers that quantify profiles of stratospheric H_2O (Nedoluha et al. 2023) and ClO (Connor et al. 2013).

Over the past half-century, our understanding of stratospheric ozone has benefited enormously from both spaceborne and suborbital assets, including observations obtained by the ground-based platforms highlighted in Fig. 3. However, suborbital instruments provide limited sampling, and the use of these data is subject to influence from atmospheric variability

that must be overcome for accurate understanding of long-term trends (Hegglin et al. 2014; Prignon et al. 2021). Nonetheless, when observations from MLS and ACE-FTS are no longer available, data from suborbital platforms will become critical to maintain and possibly expand in terms of spatial and temporal sampling.

3. The unusual recent stratosphere

The composition of Earth's stratosphere has been highly perturbed in recent years. Figure 4 displays the interannual variability of H_2O, N_2O, HCl, and O_3 at selected pressure levels in the stratosphere from 2005 through 2023. The detrended and deseasonalized VMR anomalies in the figure were computed using the MERRA-2 Stratospheric Composition Reanalysis of *Aura* MLS (M2-SCREAM) (Wargan et al. 2023); anomalies greater than three standard deviations σ above the long-term mean are colored. Over the first 15 years, the trace constituent anomaly time series shows an expected degree of variability as the only coherent set of 4σ and larger anomalies are those observed for O_3 and HCl during the cold Arctic conditions in early 2011 ("A," Fig. 4). This "business as usual" regime for stratospheric composition ended in 2019, after which a series of 4σ and larger anomalies was observed. Figure 5 presents the stratospheric aerosol optical depth (SAOD) over the same time period as Fig. 4, and it shows that many of the recent composition anomalies are linked to large increases in SAOD, as explained in more detail below. The anomalies shown in Figs. 4 and 5 serve as an organizational framework for the rest of this section.

A triad of 4σ and larger anomalies in O_3, HCl, and N_2O was observed at Northern Hemisphere (NH) midlatitudes in 2019 ("B," Fig. 4). These anomalies, first identified by Manney et al. (2022), are currently an active area of research and appear to be related to the combination and relative timing of tracer transport by the secondary circulation associated with the quasi-biennial oscillation (QBO) in variations in the strength of stratospheric winds and strong downward and poleward transport by the BDC in the winter of 2018/19. Later that year, a rare Southern Hemisphere (SH) sudden stratospheric warming occurred that was associated with large anomalies in O_3 and HCl ("C"). Then, in early 2020, unusually prolonged cold conditions in the Arctic led to large anomalies in O_3, HCl, and N_2O ("D"). For the months

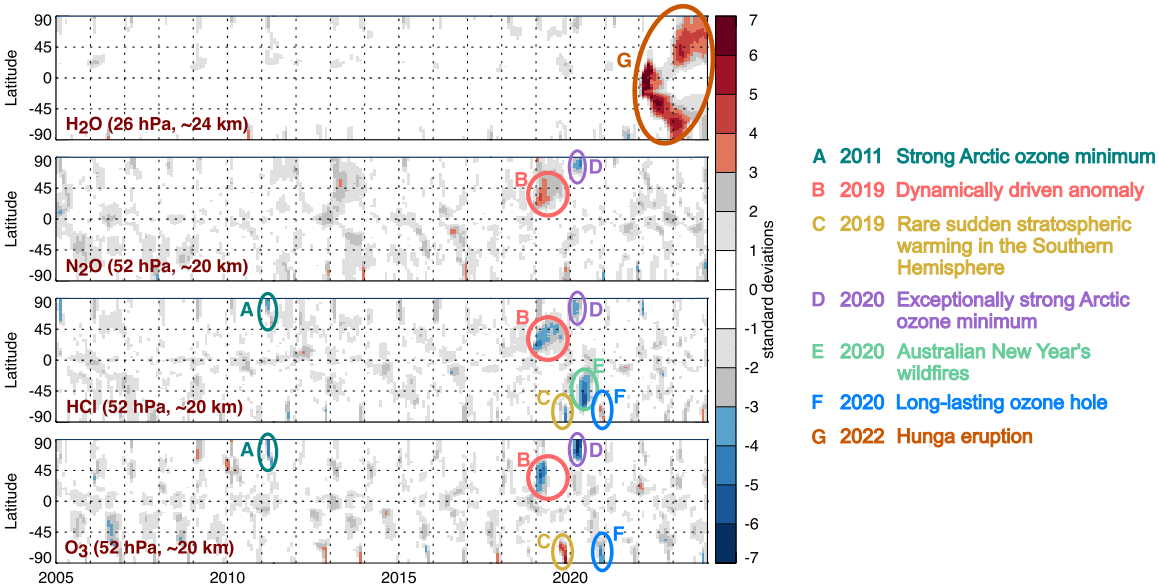

FIG. 4. Deseasonalized, detrended anomalies in time series of H_2O, N_2O, HCl, and O_3 mixing ratios at selected pressure levels, expressed in units of standard deviation from the mean σ. Anomalies greater than 3σ deviation about the long-term mean are shown using color. Anomalies of 4σ or greater are circled and denoted by letters, with the geophysical event associated with each anomaly identified at right. The analysis is based on the M2-SCREAM assimilation of MLS observations driven by assimilated meteorological fields from MERRA-2 (Wargan et al. 2023).

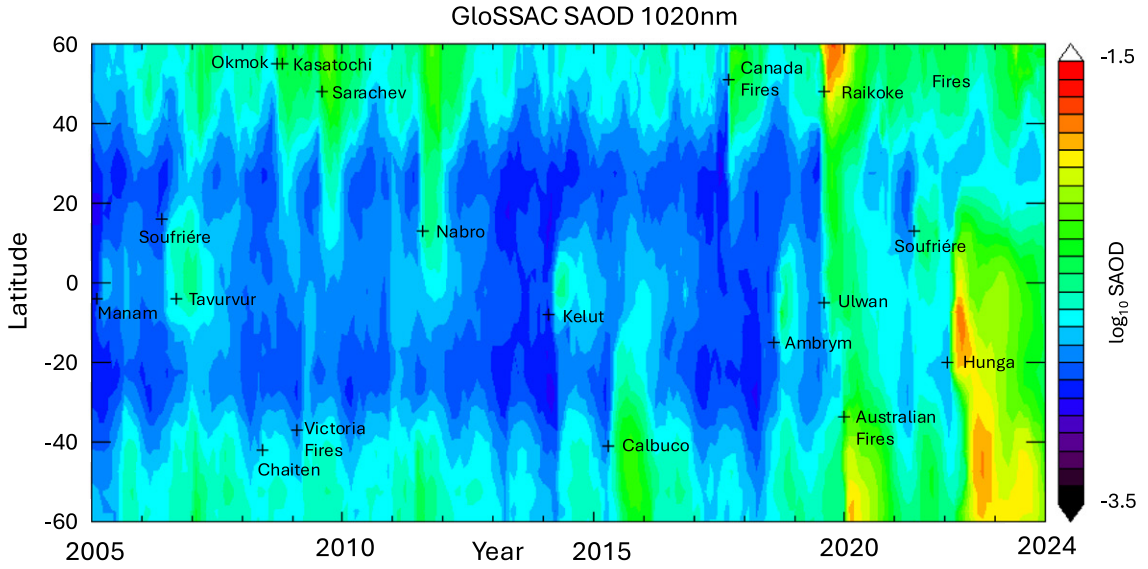

Fig. 5. Variations in SAOD at a wavelength of 1020 nm, computed based on the integration of extinction coefficients from the Global Space-Based Stratospheric Aerosol Climatology (GloSSAC) version 2.22 database (Thomason et al. 2018; Kovilakam et al. 2023). The impact of various volcanic eruptions and large wildfires on SAOD is evident, as marked.

following the Australian New Year's fires that began in late 2019, a large negative anomaly in HCl was observed throughout the SH midlatitudes ("E"). The Antarctic ozone hole in 2020 was exceptionally deep, with negative anomalies in O_3 and positive anomalies in HCl ("F"). While 2021 was a relatively quiet year, the extraordinary eruption of Hunga in January 2022 injected an enormous amount of water vapor deep into the SH stratosphere and mesosphere, resulting in 4σ and larger anomalies in H_2O that began in the tropics, expanded throughout SH midlatitudes, and eventually reached both poles ("G").

Many of these anomalies occur in polar regions and are observed for H_2O, N_2O, HCl, and O_3. As noted above, when ACE-FTS and MLS cease to operate, measurements of almost all of these species will be extremely limited in the polar regions. Profiles of H_2O will be sparse in both space and time for other regions of the stratosphere, and profiles of tracers such as N_2O and halogens such as HCl, $ClONO_2$, and ClO will not exist for the global stratosphere.

a. Australian wildfires. The Australian wildfires of late 2019 and early 2020 injected massive amounts of aerosol into the SH midlatitude stratosphere (Fig. 5) (Khaykin et al. 2020), resulting in a reduction in TCO between 30° and 60°S that reached its peak during May–August 2020 at about 6–10 Dobson units (DUs) below the long-term mean (Rieger et al. 2021; Strahan et al. 2022). These wildfire aerosols warmed the stratosphere by several degrees Celsius and resulted in a near-immediate alteration of stratospheric winds (Kablick et al. 2020), which in turn led to dynamically induced reductions in TCO (Santee et al. 2022; Strahan et al. 2022). Declines in O_3 relative to N_2O served as the key observational constraint for estimating the decline in TCO caused by changes in stratospheric transport.

Figure 6 shows observations of ClO and HCl from MLS and $ClONO_2$ from ACE-FTS in the SH midlatitude stratosphere, with data collected in 2020 highlighted in red. Substantial enhancements of ClO and $ClONO_2$ are apparent, as is the suppression of HCl (Santee et al. 2022; Strahan et al. 2022). Models run with the standard hydrolysis of N_2O_5 on sulfate aerosols and other heterogeneous processes that typically are important only under cold conditions failed to capture the magnitude of the observed response (Strahan et al. 2022). These enhancements in ClO are of the same magnitude as the increase that followed the 1991 eruption of Mount Pinatubo (Fahey et al. 1993) and therefore are large enough to result in significant chemical

loss of stratospheric ozone (Salawitch and McBride 2022).

Solar infrared spectra obtained by ACE-FTS proved to be the key to explaining the enhancements of ClO and $ClONO_2$ and suppression of HCl observed over broad regions of the SH midlatitude stratosphere in the months following the Australian wildfires. Bernath et al. (2022) showed the presence of strong absorption features in SH midlatitude spectra due to C=O, CH, and OH stretching modes which are characteristic of organic aerosol. Solomon et al. (2023) proposed that HCl would dissolve in these organic aerosols and undergo a series of heterogeneous chemical reactions that could account for the observed reduction in HCl and enhancements of $ClONO_2$ and ClO (blue lines, Fig. 6). Their model simulation accounting for the dissolution and subsequent reaction of HCl shows that this chemical change, caused by Australian wildfire aerosols, also contributed to the observed decline of TCO over broad regions of the SH midlatitude stratosphere.

The current consensus, summarized by Chipperfield and Bekki (2024), is that the decline in TCO following the Australian wildfires was likely caused by a combination of dynamics and chemistry. They also note that the physical state (i.e., liquid, glassy, or solid) and detailed composition of wildfire particles are not known and that future laboratory measurements will be needed to advance our understanding of the impact of wildfires on stratospheric composition. Nevertheless, observations provided by ACE-FTS and MLS identified this critical—and unforeseen—chemical mechanism and were essential to achieving our current level of understanding. If large wildfires continue to impact the stratosphere during the future data desert, the causes of any resulting declines in stratospheric ozone will be

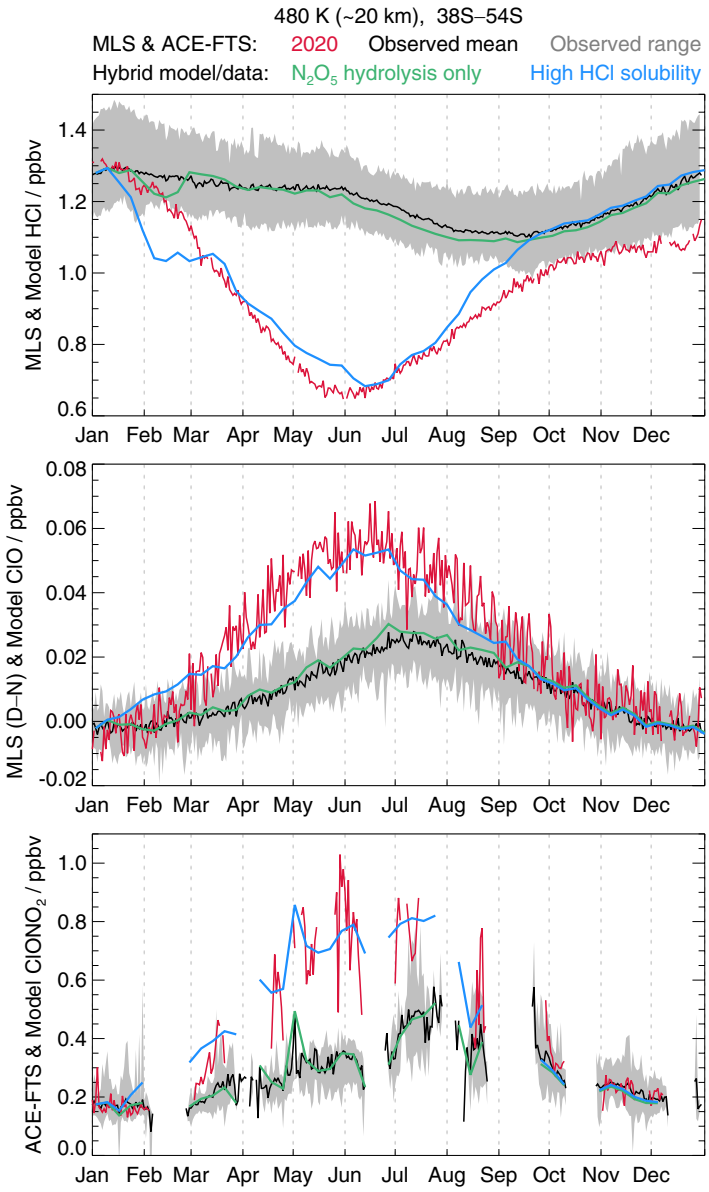

FIG. 6. Daily (day and night) averaged mixing ratios of HCl, ClO, and $ClONO_2$ measured in 2020 (red), as well as the climatological mean (black) and range (gray) over 2005–19 obtained by MLS (HCl and ClO) and ACE-FTS ($ClONO_2$) at the 480-K potential temperature level between 38° and 54°S. For ClO, the 24-h-averaged values are approximated as half of the day–night differences to reduce measurement biases (and assuming zero ClO at night). Also shown are hybrid modeled/measured quantities computed by adding model-calculated daily averaged anomalies in the three chlorine species to the respective observed climatological means from MLS and ACE-FTS. For the green lines, the anomalies are taken from a simulation using only N_2O_5 hydrolysis on aerosols and other heterogeneous processes in standard models; for the blue lines, they are taken from a simulation that includes enhanced solubility of HCl on organic aerosols and subsequent heterogeneous reactions of HCl. Adapted from Santee et al. (2022) and Solomon et al. (2023).

impossible to observationally determine due to the lack of high-spectral-resolution infrared solar spectra along with few or no observations of ClO, $ClONO_2$, HCl, and N_2O. This concern is heightened further by the likelihood that future drought and changes in atmospheric stability due to global warming will lead to an increase in the frequency of extreme wildfires, in Australia (Di Virgilio et al. 2019) as well as in many other fire-prone regions (Holden et al. 2018; Pausas and Keeley 2021).

Stratospheric circulation changes may also be causally linked to the Australian wildfires. Studies have suggested that the hot, dry weather conditions in Australia during the austral summer of 2019/20 might, in part, be a response of the tropospheric climate system to the weak stratospheric polar vortex in 2019 that is marked by the yellow circles (C) in Fig. 4 (Lim et al. 2019, 2021; Baldwin et al. 2021). If a sudden stratospheric warming did indeed foreshadow an event as catastrophic as the 2019/20 Australian wildfires, then the types of measurements discussed throughout this article could have a much greater impact than is commonly appreciated.

b. Hunga eruption. The eruption of the undersea Hunga Tonga–Hunga Ha'apai (Hunga) volcano (20.54°S, 175.38°W) on 15 January 2022 injected enormous amounts of H_2O into the stratosphere along with significant amounts of sulfur dioxide (SO_2) (Khaykin et al. 2022; Millán et al. 2022; Vömel et al. 2022). MLS stratospheric H_2O profiles revealed that the mass of H_2O injected into the stratosphere by this eruption was equivalent to about 10% of the mass of H_2O present in the global stratosphere prior to the eruption. This amount vastly exceeds the injection of H_2O by other volcanoes over the modern satellite record (1979 to the present) (Millán et al. 2022; Vömel et al. 2022). The unique nature of this event was due to a combination of its large volcanic explosive index (VEI) of 5.8, as well as the submarine setting of the eruption (Khaykin et al. 2022; Witze 2022).

The top panel of Fig. 4 shows that at the 26-hPa pressure level, the extreme enhancement of H_2O was confined to the tropics for the first few months after the eruption and then spread throughout SH midlatitudes (Schoeberl et al. 2022; Santee et al. 2023; Wilmouth et al. 2023). However, the strong winds that define the Antarctic polar vortex prevented penetration of the H_2O plume into the vortex during 2022 (Manney et al. 2023). MLS data in Fig. 4 show that the progression of enhanced H_2O into polar regions of both hemispheres occurred during 2023 (Santee et al. 2024; Wohltmann et al. 2024; Zhang et al. 2024).

Figure 7 shows anomalies of stratospheric H_2O from 2005 to the present in the tropics, as recorded by MLS and SAGE III/ISS. This record of stratospheric H_2O, termed the "tape recorder"

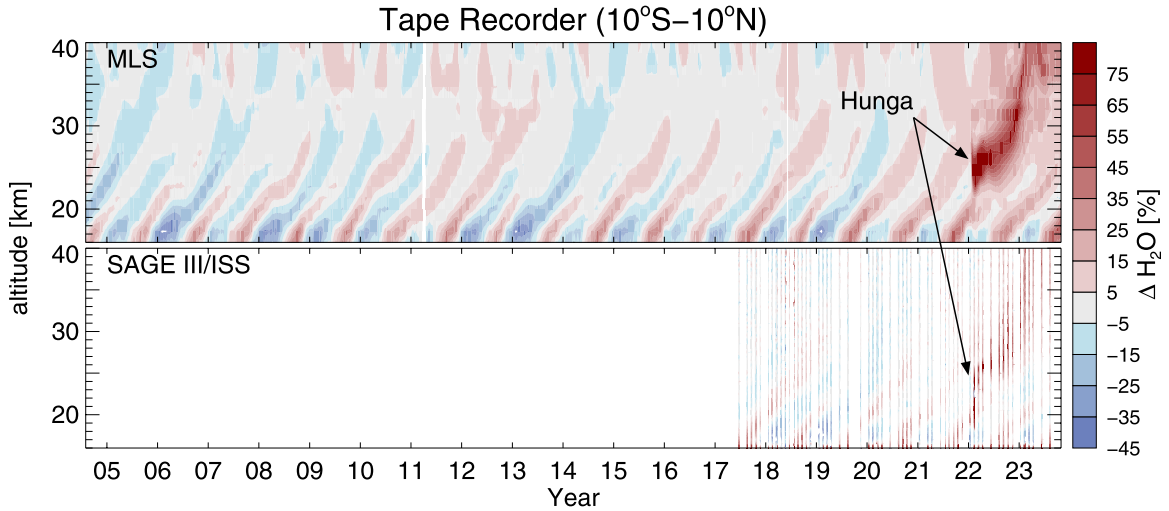

Fig. 7. Zonal-mean H_2O anomalies (%) in the tropics (10°S–10°N), as a function of altitude and time, measured by *Aura* MLS and SAGE III/ISS. Update to Fig. 5 of Millán et al. (2022).

by Mote et al. (1996), is directly linked to the impact of variations of tropical tropopause temperature on stratospheric humidity (Randel and Park 2019; Konopka et al. 2022; Millán et al. 2024) as well as the strength and variability of the BDC (Flury et al. 2013). The ability to observationally define the perturbation to stratospheric H_2O by MLS, which provides daily near-global measurements, stands in contrast to the relatively sparse record provided by solar occultation instruments such as SAGE III/ISS (see Fig. 3), which first sampled the Hunga plume 3–5 days after the eruption, then not again until day 23, and then on days 30–33.

The Hunga eruption altered the temperature, transport, and chemistry of the stratosphere in a manner that has been the subject of many recent studies. The impact of this eruption on the characteristics of stratospheric aerosol loading has been well documented by both balloon (Asher et al. 2023; Evan et al. 2024) and spaceborne (Kloss et al. 2022; Legras et al. 2022; Taha et al. 2022; Knepp et al. 2024) instruments that will continue to operate for the foreseeable future, with the exception of the *CALIOP* spaceborne lidar onboard the NASA *CALIPSO* satellite, which ceased operations on 1 August 2023 after a remarkable 17-yr journey of discovery. Stratospheric lidar aerosol measurements will continue with the ESA Earth Cloud, Aerosol, and Radiation Explorer (EarthCARE) (Illingworth et al. 2015) that began operations in 2024.

However, a quantitative understanding of the impact of the Hunga eruption on stratospheric O_3 has relied on analyses of data acquired by MLS and ACE-FTS. Enhanced levels of stratospheric H_2O resulted in a 2–3-K cooling throughout the global upper stratosphere (Coy et al. 2022; Schoeberl et al. 2022; Wang et al. 2023), with largest effects in May 2022 of about 5-K cooling at 20 hPa between 20° and 25°S (Fleming et al. 2024). Our theoretical understanding of the stratospheric cooling induced by the Hunga eruption is guided by reanalyses and by models initialized with MLS profiles of H_2O (Coy et al. 2022; Wang et al. 2023; Fleming et al. 2024). As was the case for the Australian wildfires, the reductions in extrapolar TCO that resulted from the Hunga eruption were due to a combination of dynamical and chemical effects (Santee et al. 2023; Wang et al. 2023; Wilmouth et al. 2023; Fleming et al. 2024). Analysis of monthly mean anomalies of VMRs of O_3 versus N_2O at various latitudes and altitudes was the essential element for quantifying the contribution of Hunga-induced changes in stratospheric transport to reductions in TCO over broad regions of the SH (Santee et al. 2023; Wilmouth et al. 2023). Measurements of stratospheric profiles of halogens and tracers from MLS and ACE-FTS also enabled diagnosis of the effect of the Hunga eruption on stratospheric chemistry, both through elevated OH due to the oxidation of H_2O, followed by enhancements of ClO due to the reaction of OH with HCl (Zhu et al. 2022, 2023; Wilmouth et al. 2023; Fleming et al. 2024; Zhang et al. 2024), and through heterogeneous chemistry on volcanic aerosols (Santee et al. 2023; Zhang et al. 2024). Impacts of the Hunga eruption on the Antarctic ozone hole have also been investigated using measurements from MLS (Manney et al. 2023; Fleming et al. 2024; Santee et al. 2024; Wohltmann et al. 2024; Zhou et al. 2024). Should an eruption with a VEI approaching the magnitude of Hunga occur during the upcoming data desert, the lack of profiles of halogens and tracers throughout the global stratosphere will hamper the quantification of the factors responsible for the associated changes to stratospheric composition.

4. Ozone layer recovery

a. Midlatitude ozone. The recovery of ozone from depletion by anthropogenic halogens is not occurring as fast as had been expected, particularly for the NH midlatitude lower stratosphere (Ball et al. 2018; Chipperfield et al. 2018; Wargan et al. 2018; Orbe et al. 2020; Weber et al. 2022; Bednarz et al. 2023b; Chipperfield and Bekki 2024). Due to the success of the Montreal Protocol, the surface abundances of CFCs and most other ODSs have been declining over the past two decades, and stratospheric halogen loading started to decrease

after the late 1990s (WMO 2022). Everything else being equal, a rise of TCO at NH midlatitudes should have been observed over the past decade (Oman et al. 2010; Eyring et al. 2013; Dhomse et al. 2018; Keeble et al. 2021). However, trends in TCO between 35° and 60°N have been negligible from 1996 to the present (a change of 0.0% ± 0.7% decade^{-1}), in contrast to 35°–60°S, where TCO has been rising at a rate of 0.8% ± 0.7% decade^{-1}, close to the expected rate of recovery (WMO 2022).

Several hypotheses have been advanced to explain the slower-than-expected recovery of ozone at NH midlatitudes. These include dynamical influences on ozone such as QBO variations in the strength of stratospheric winds, structural changes in the BDC, and changes in dynamical patterns such as the Arctic Oscillation (Ball et al. 2018, 2020; Chipperfield et al. 2018; Wargan et al. 2018; Coldewey-Egbers et al. 2020; Orbe et al. 2020). Chemical effects such as the influence of a class of compounds called very-short-lived chlorocarbons (VSL-Cl), which have rising emissions (Fang et al. 2019; An et al. 2021) and are not regulated by the Montreal Protocol, have also been proposed as a factor in the delayed recovery of ozone at NH midlatitudes (Hossaini et al. 2024; Chipperfield et al. 2020; Bednarz et al. 2023b; Villamayor et al. 2023).

A comprehensive analysis of the total chlorine budget is an important element of our ability to relate surface emissions of ODSs to the effect of these anthropogenic halogens on the ozone layer. Nassar et al. (2006) examined ACE-FTS observations of a suite of organic and inorganic chlorine species in five latitude bands over a variety of stratospheric altitudes and concluded that there was evidence of an initial decline in global stratospheric chlorine in 2004 consistent with both stratospheric circulation and the time lag necessary for the transport of chlorine from the surface to the stratosphere. However, the rate of the decline in inorganic chlorine in the upper stratosphere since 2004 is uncertain. Nearly the entire complement of inorganic chlorine in the upper stratosphere is present as HCl. Bernath and Fernando (2018) concluded based on linear regression analysis that upper-stratospheric HCl between 60°S and 60°N, as measured by ACE-FTS, was declining over the period 2004–17 in a manner quantitatively consistent with the decline in surface abundances of CFCs and other ODSs regulated by the Montreal Protocol. Conversely, Hossaini et al. (2019) and Bednarz et al. (2022) analyzed similar measurements using global models and concluded that upper-stratospheric HCl is declining more slowly than expected based solely on long-lived ODSs, as shown in Fig. 8, and that trends in HCl measured by ACE-FTS are best explained by allowing for the impact of the unregulated VSL-Cl gases on the stratospheric chlorine budget.

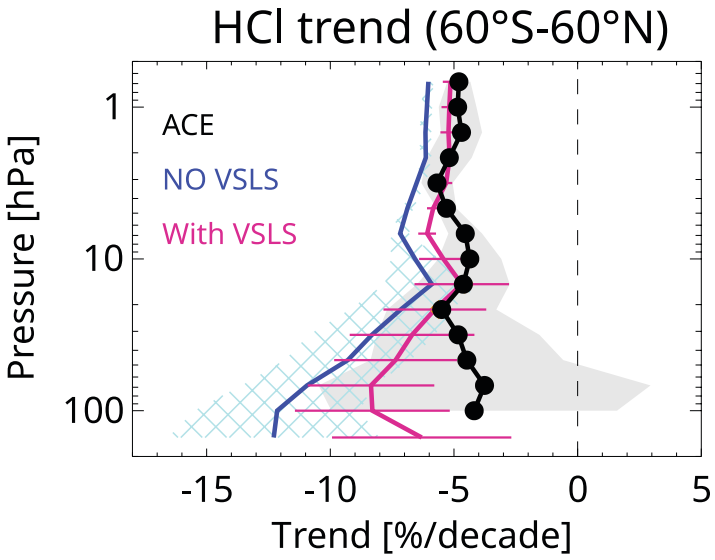

Fig. 8. Impact of VSL-Cl on stratospheric HCl trends. Mean HCl trends (2004–17) calculated for latitudes 60°S–60°N. Modeled HCl trends (% per decade) with and without VSL-Cl from the Toulouse Off-Line Model of Chemistry and Transport (TOMCAT) 3D chemical transport model. For the long-lived chlorine source gases, the model used global-mean surface mixing ratios based on observations. Observed HCl trends are derived from the ACE-FTS satellite instrument. The 2σ trend uncertainties are denoted by the horizontal bars, shading, and hatching. The inclusion of VSL-Cl increases the HCl trend, especially in the lower stratosphere, bringing the model into better agreement with the observations. Update to Fig. 7a of Hossaini et al. (2019).

Upper-stratospheric chlorine is currently measured by both MLS (Froidevaux et al. 2006, 2022) and ACE-FTS (Bernath and Fernando 2018). The future loss of these measurements will impede our ability to connect changes in the surface abundances of CFCs, other ODSs, and VSL-Cl to the ultimate driver of chemical loss of ozone, which is the abundance of stratospheric chlorine. The impending data desert will occur at an especially precarious time for monitoring the evolution of stratospheric chlorine because

1) revisions to projections of future abundances of the 16 principal ODSs, due to updates in leakage rates from allowed use as feedstock for the manufacture of other compounds together with updates to the emissions from existing and future equipment ("banks"), show that the future decline of stratospheric chlorine will be considerably slower than previously expected (Lickley et al. 2021, 2024; Li et al. 2024);
2) ground-based observations reveal a rise in the atmospheric abundances of five minor CFCs used mainly as feedstock for the production of other chemicals that, should this rise continue, will counteract some of the benefits gained under the Montreal Protocol (Western et al. 2023);
3) the atmospheric abundances of most VSL-Cl gases, which are not regulated by the Montreal Protocol, are continuing to rise (Fang et al. 2019; Hossaini et al. 2019, 2024; Chipperfield et al. 2020; An et al. 2021; Bednarz et al. 2022; Villamayor et al. 2023); and
4) airborne measurements, augmented by MLS observations of CO, show significant transport to the stratosphere of five major VSL-Cl gases by the East Asian summer monsoon, including the first quantification of stratospheric injection of relatively large amounts of 1,2-dichloropropane ($C_3H_6Cl_2$) (Pan et al. 2024).

As noted above, the strength of the BDC is projected to increase, which should accelerate the recovery of TCO at midlatitudes of both hemispheres and lead to a permanent reduction in TCO in the tropics (Butchart et al. 2006, 2011; Garcia and Randel 2008; Abalos et al. 2021). During the imminent data desert, sporadic measurements of profiles of transport tracers such as N_2O and CH_4 will likely not be sufficient to quantify how the BDC is changing, a substantial limitation given the large range of theoretical projections of the magnitude of the future increase in the strength of the BDC and the fact that the predicted strengthening of the BDC has not yet been conclusively observed (Butchart et al. 2006; Li et al. 2008; Abalos et al. 2021). The picture is further complicated by the chemical impacts of N_2O and CH_4, whose abundances are increasing in the stratosphere. Whereas future increases in CH_4 are projected to lead to an increase in TCO at midlatitudes (Fleming et al. 2011; Revell et al. 2012), future increases in N_2O are projected to lead to a decrease in TCO (Ravishankara et al. 2009; Eyring et al. 2013). Unraveling the impacts of CH_4 and N_2O on ozone is particularly complicated due to nonlinear aspects of stratospheric chemistry (Isaksen et al. 2014; Revell et al. 2015).

The continued recovery of the ozone layer (Oman et al. 2010; Dhomse et al. 2018; Keeble et al. 2021) faces a number of other threats. First, there is renewed interest in commercial supersonic transport aircraft with the potential for substantial impacts on stratospheric composition, including reductions in O_3, especially in the tropics, and increases in stratospheric H_2O and black carbon aerosols, which together are estimated to result in a warming of Earth's surface (Zhang et al. 2023). Second, an expected order-of-magnitude increase in space debris in the stratosphere from the burn-up of satellites and rocket stages during reentry will increase the metallic content of stratospheric aerosols (Murphy et al. 2023) and has the potential to cause ozone depletion (Ferreira et al. 2024). In addition, exhaust associated with an enormous future increase in the number of satellite launches (58 000 launches by 2030, compared to 5500 satellites in orbit as of spring 2022) (Howard and Von Ah 2022) could add black carbon to the stratosphere (Ross et al. 2010), which could increase stratospheric

temperatures, alter atmospheric circulation, and cause a substantial reduction in TCO over NH midlatitudes (Maloney et al. 2022). The current spaceborne fleet of instruments provides an important observational baseline. During the imminent data desert, future impacts on ozone of supersonic transport, rocket launches, and vehicle reentry will be difficult to quantify.

Finally, tropospheric pollution from both industrial processes and biomass burning can be injected into the stratosphere, including compounds such as CO, HCN, CH_3Cl, acetonitrile (CH_3CN), and methanol (CH_3OH) measured by MLS and ACE-FTS (Bernath 2006; Schwartz et al. 2020). Analyses of MLS and ACE-FTS measurements have revealed that the summer monsoon circulation in the upper troposphere/lower stratosphere that spans the region from East Asia to the Middle East provides an efficient pathway for pollutants to enter the global stratosphere (Li et al. 2005; Fu et al. 2006; Park et al. 2007, 2008; Randel et al. 2010). Figure 9 shows the large perturbations in cloud ice water content (IWC) (an indicator of the occurrence of deep convection), CO, and CH_3Cl routinely observed by MLS that are associated with the Asian summer monsoon (Santee et al. 2017). The CO and CH_3Cl enhancements are clearly related to pollutants emitted by industrial activities and biomass burning at the surface, based upon analyses of measurements from MLS and ACE-FTS as well as profiles of CO obtained by the spaceborne Measurements of Pollution in the Troposphere (MOPITT) instrument that extend into the lower troposphere (Jiang et al. 2015; Smoydzin and Hoor 2022). There are no plans in place to continue spaceborne observations of tracers of tropospheric pollution, from which stratospheric injection is inferred. Again, the current suite of spaceborne instruments provides an observational baseline, and once MLS, ACE-FTS, and MOPITT cease operations, the future impact of pollution from industrial processes and biomass burning on the ozone layer will be difficult to directly characterize from observations.

b. Polar ozone. Model simulations project that the size and depth of the Antarctic ozone hole will decrease over the coming decades in a manner that largely follows future declines in the abundance of stratospheric halogens (Oman et al. 2010; Eyring et al. 2013; Dhomse et al. 2018; Keeble et al. 2021). The size of the ozone hole varies from year to year, largely due to meteorological influences, such as the rare SH sudden stratospheric warming that occurred in 2019 (Safieddine et al. 2020; Wargan et al. 2020; Bodeker and Kremser 2021; Klekociuk et al. 2021), as well as exceptionally cold and long-lasting vortices in 2020–23 (Grytsai et al. 2022; Klekociuk et al. 2022; Kramarova et al. 2024). For O_3 and HCl at 52 hPa, MLS observed 4σ and larger anomalies in 2019, 2020, and 2023 (Fig. 4).

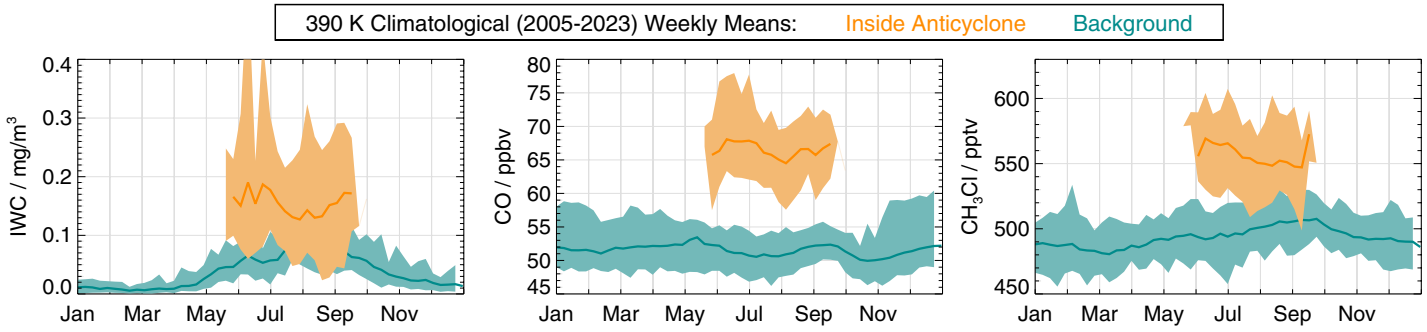

Fig. 9. Weekly averages over the annual cycle of MLS measurements of cloud IWC (a proxy for deep convection), CO, and CH_3Cl within the 15°–45°N latitude band at 390-K potential temperature, which corresponds to ~15–17-km altitude in the region of the Asian monsoon during boreal summer. Dark orange lines represent climatological averages calculated over the period 2005–23 within the anticyclonic monsoon circulation during the boreal summer season when it is defined; dark teal lines represent averages calculated over the latitude domain in the remaining portion of the hemisphere excluding the area of the Asian summer monsoon circulation. Paler shading represents the ranges of values measured over 2005–23 in the respective regions. Update to Fig. 3 of Santee et al. (2017).

Volcanic eruptions can increase the depth and size of the Antarctic ozone hole as the ensuing enhancement in aerosol surface area facilitates chlorine activation (Hofmann and Solomon 1989). The April 2015 eruption of Calbuco in southern Chile led to the largest and deepest ozone hole observed during the modern satellite era, primarily due to sulfate aerosol that was transported into the Antarctic polar vortex (Solomon et al. 2016; Stone et al. 2017; Zhu et al. 2018). The deep ozone hole in 2021 has also been linked to the eruption of La Soufrière (Yook et al. 2022).

The severity of polar ozone depletion exhibits much more interannual variability in the Arctic compared to the Antarctic (Rex et al. 2004, 2006; Tilmes et al. 2004; Weber et al. 2011; von der Gathen et al. 2021) and is driven by the larger variability in NH meteorological conditions. As stated in the introduction, Arctic winter–spring periods with long-lasting cold conditions exhibit severe chemical loss of ozone (Manney et al. 2011, 2020; Griffin et al. 2019; Lawrence et al. 2020; Wohltmann et al. 2020; Feng et al. 2021; Grooß and Müller 2021). The increased variability of TCO in Arctic spring arises from year-to-year differences in both dynamics and chemical loss due to anthropogenic halogens (Hadjinicolaou and Pyle 2004; Tegtmeier et al. 2008; Calvo et al. 2015). The large natural interannual variability of Arctic ozone has so far precluded the identification of a statistically significant trend over the past two decades (WMO 2022).

Analysis of seasonal declines in O_3 versus transport tracers such as N_2O and CH_4 constitutes an important tool for quantifying the impact of chemical loss on TCO, particularly within the Arctic vortex (Salawitch et al. 2002; Müller et al. 2005; Tilmes et al. 2006). Profiles of N_2O provide an empirical measure of diabatic descent within the polar vortex, which is necessary to distinguish dynamical and chemical impacts on O_3, especially in the Arctic (Manney et al. 2011, 2020; Feng et al. 2021). Some studies suggest that particularly cold Arctic winter–spring periods conducive to severe chemical ozone loss will become more common in the future, as stratospheric temperatures decrease with climate change (Rex et al. 2004, 2006; von der Gathen et al. 2021). During the imminent data desert, spaceborne profiles of vertically resolved measurements of stratospheric halogens and transport tracers will not be available. Spaceborne profiles of O_3 will also not be available during the critical period of vortex formation, which occurs during polar night. Therefore, the diagnosis of the causes of interannual variations in ozone within the Arctic and Antarctic polar vortices will be forced to rely on simulated profiles of O_3. Most importantly, our ability to empirically quantify the degree of chemical ozone loss in persistently cold winters in either hemisphere, as well as the impact of future volcanic eruptions on chemical (Solomon et al. 2016) and dynamical (Ivy et al. 2017) conditions in the polar regions, will be severely compromised.

c. Surface climate. The long-term change in stratospheric water vapor has been shown to impact decadal trends in the rate of global warming (Solomon et al. 2010). Future increases in stratospheric H_2O may constitute an important climate feedback that might be of the same order of magnitude as feedbacks involving surface albedo and tropospheric clouds (Banerjee et al. 2019; Tao et al. 2023). These analyses rely on homogenized, long-term records of stratospheric H_2O from a series of limb-profiling satellite instruments, which currently utilize measurements from MLS as the primary daily near-global source of data (Froidevaux et al. 2015; Davis et al. 2016). The accurate quantification of future climate change on decadal and centennial time scales is a coupled chemistry–climate problem that requires continuous measurements of stratospheric profiles of ozone, water vapor, and aerosols (IPCC 2021).

Volcanic eruptions that inject sulfate aerosols into the stratosphere can also impact climate, not only on annual time scales but also on decadal time scales, depending upon the sequence of eruptions (Solomon et al. 2011; Marshall et al. 2022). The eruption of Mount

Pinatubo injected nearly 20 Tg of SO_2 into the stratosphere (Bluth et al. 1992), which led to a reduction in global-mean surface temperature (GMST) between about 0.1° and 0.4°C (Santer et al. 2001; Thompson et al. 2009; Canty et al. 2013; Fujiwara et al. 2020). In contrast, the Hunga eruption injected between 0.5 and 0.7 Tg of SO_2 into the stratosphere (Carn et al. 2022; Sellitto et al. 2022; Duchamp et al. 2023) and is estimated to have resulted in a cooling of less than about 0.04°C of Earth's surface in the SH in 2022 (Schoeberl et al. 2023). This small net cooling occurred because the attenuation of solar radiation by aerosols was partly canceled by heating due to the large increase in stratospheric water vapor. Without observations of stratospheric water vapor and aerosols from MLS, SAGE III/ISS, and OMPS-LP, it would have been difficult to diagnose the climate impact of Hunga.

5. Geoengineering for climate change mitigation

There is increasing dialog regarding the possibility of using stratospheric aerosol injection (SAI) as a means to slow the rate of global warming, as noted in reports on SAI by the U.S. National Academy of Sciences in 2015 (NAS 2015) and 2021 (NAS 2021), as well as a chapter on this topic in the most recent Scientific Assessment of Ozone Depletion report (Haywood et al. 2022). It is nearly inconceivable that the world is facing an imminent data desert with respect to monitoring stratospheric composition and the recovery of the ozone layer, even as discussions around the possibility of geoengineering the climate by SAI are ongoing (Tilmes et al. 2024).

The actual response of stratospheric ozone to the injection of sulfate or other types of aerosols depends on details of the chemical and dynamical effects of such an action (Haywood et al. 2022). Injection of sulfate aerosols into the stratosphere has the potential to delay the recovery of the ozone layer from depletion by anthropogenic halogens in the polar regions of both hemispheres (Tilmes et al. 2008; Pitari et al. 2014; Lee et al. 2021) and over the rest of the global stratosphere (Heckendorn et al. 2009; Tilmes et al. 2012; Robrecht et al. 2021). The 2006 paper that invigorated debate among the world's scientists and policymakers about climate intervention used the response of TCO and GMST to the 1991 eruption of Mount Pinatubo as an analogy for the effects of SAI (Crutzen 2006). Figure 10 shows the response of the GMST anomaly to the 1991 eruption of Mount Pinatubo and the earlier

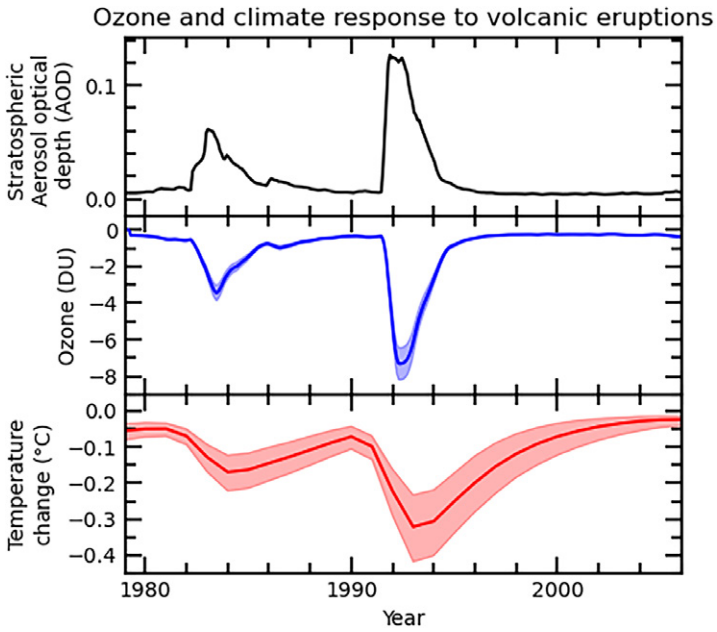

FIG. 10. Time series of SAOD, the anomaly in TCO (ΔO_3) between 60°S and 60°N, and the anomaly in GMST (ΔT) following the volcanic eruptions of El Chichón and Mount Pinatubo in 1982 and 1991, respectively. The monthly SAOD time series is based on integration of extinction coefficients from the GloSSAC v2 database (Thomason et al. 2018; Kovilakam et al. 2023). The ΔO_3 time series is the computed impact of SAOD on ΔO_3 found for a multiple linear regression of monthly TCO averaged over 60°S–60°N vs the following terms: equivalent effective stratospheric chlorine for 3-yr-old air, total solar irradiance, SAOD, the QBO in the zonal-mean wind in the tropical lower stratosphere, and El Niño–Southern Oscillation, as in Fig. 3-1 of Chipperfield et al. (2007). The ΔO_3 time series is smoothed with a 6-month running mean; the shaded region defines the 2σ uncertainty based on a conditional regression. The time series of ΔT and the 2σ uncertainties represented by the shaded region are obtained from the model output used to construct Fig. 7.8 of the IPCC Sixth Assessment Report (IPCC 2021).

eruption of El Chichón, as well as the TCO anomaly between 60°S and 60°N found using a standard regression method. While stratospheric halogen loading is now somewhat lower than at the time of the El Chichón and Mount Pinatubo eruptions, if SAI were to be used for "peak shaving" of global temperature (Haywood et al. 2022) in the near future, anthropogenic chlorine would still be much higher than at the time of the onset of the Antarctic ozone hole, and chlorine-catalyzed ozone loss would therefore be expected. Regardless, the ozone decreases that followed these eruptions, which are straightforward to quantify in the TCO data record, serve as an important starting point for discussion of the consequences of deliberate SAI. Were SAI to be implemented at a magnitude that rivals the stratospheric injection of sulfur following the eruption of Mount Pinatubo, the data shown in Fig. 10 suggest that ozone depletion could occur over densely populated regions of the globe. Should SAI be undertaken while we are in the midst of the data desert, our ability to assess the chemical and dynamical response of the stratosphere to such climate intervention efforts will be severely limited.

6. Concluding thoughts

The stratosphere is not a solved problem. The past few years have marked an era of discovery and new understanding, greatly enabled by the portfolio of observations from the ACE-FTS and MLS instruments. The atmospheric science community now faces an impending data desert as ACE-FTS is over 20 years old and MLS nears the end of its operational lifetime. This data gap will occur at a time when the recovery of stratospheric ozone at NH midlatitudes has stalled and just after the impacts on stratospheric ozone of wildfires and an undersea volcanic eruption have been quantified for the first time. Future impacts to the recovery of the ozone layer from a wide range of tropospheric pollutants, changes in the strength of the BDC in response to increasing greenhouse gases (GHGs), the possibility of cold Arctic winters getting colder, the emerging threats posed by the potential for increasing extreme wildfires and space debris, and the specter of geoengineering for climate change mitigation through SAI will be difficult to quantify in the absence of the types of observations provided by ACE-FTS and MLS. Similarly, our ability to understand future changes to stratospheric water vapor and its attendant chemical and climate impacts will be diminished. Routes to ensuring long-term continuity for these measurements are unclear. Upon loss of the measurement capability provided by these instruments, our ability to understand the evolution of stratospheric ozone and water vapor and the wide-reaching impacts on human health and Earth's climate system will be severely hindered. While specific details of future measurement requirements are beyond the scope of this publication, we suggest that the atmospheric science community begin formally developing requirements for future spaceborne observations of stratospheric composition. Such requirements should target (i) continuous measurement of long-term trends in stratospheric composition focused on the "health" of the ozone layer, (ii) interactions between the ozone layer and Earth's climate system, and (iii) unexpected events that could cause significant departures from predicted behavior such as a particularly severe ozone hole or reductions in total column ozone over broad latitudinal regions due to wildfires or volcanoes. Finally, the future observing system should be capable of monitoring solar radiation management by SAI, including the identification of the geographic origin and chemical nature of any possible future unannounced enhancement of the stratospheric aerosol layer to mitigate global warming.

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Data availability statement. Data from *Aura* MLS are available at https://disc.gsfc.nasa.gov/datasets?page=1&keywords=AURA%20MLS, and data from *SCISAT-1* ACE-FTS are available at https://borealisdata.ca/dataverse/ace-fts_data_quality. Output from M2-SCREAM is at https://disc.gsfc.nasa.gov/datasets?keywords=M2-SCREAM&page=1 and the GloSSAC climatology of stratospheric aerosol properties is at https://asdc.larc.nasa.gov/project/GloSSAC. Finally, the volcanically induced temperature anomaly shown in Fig. 10 was obtained from https://data.ceda.ac.uk/badc/ar6_wg1/data/ch_07/ch7_fig08/v20220721.

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