4. STRATOSPHERIC OZONE—M. Weber, W. Steinbrecht, C. Arosio, R. van der A, S. M. Frith, J. Anderson, L. M. Ciasto, M. Coldewey-Egbers, S. Davis, D. Degenstein, V. E. Fioletov, L. Froidevaux, D. Hubert, D. Loyola, C. Roth, A. Rozanov, V. Sofieva, K. Tourpali, R. Wang, and J. D. Wild

Ninety percent of atmospheric ozone resides in the stratosphere with a maximum in the lower stratosphere. Stratospheric ozone protects Earth's biosphere from harmful ultraviolet (UV) radiation. Increases in anthropogenic ozone-depleting substances (ODS) thinned stratospheric ozone until the mid-1990s. The phase-out of ODS, mandated by the Montreal Protocol in the late 1980s (section 2g2), slowed stratospheric ozone loss, with some regions now showing a slow recovery. In addition, the rate and even the sign of long-term ozone changes depend on changes in chemical composition and stratospheric circulation caused by increasing concentrations of long-lived greenhouse gases (LLGHG) and varies by region and altitude. The clearest signs of ozone recovery related to ODS changes are evident in the upper stratosphere (WMO 2018).

The annual mean total ozone distribution in 2021 (Plate 2.1x) shows generally negative ozone global anomalies, except for two bands centered near 20° latitude on both sides of the equator, where ozone is higher by about 5 DU than the decadal mean (1998–2008). This pattern (low ozone in the inner tropics and high ozone in the outer tropics) is typical during the easterly wind shear phase of the quasi-biennial oscillation (QBO-east). During QBO-east, the meridional stratospheric circulation is generally stronger, resulting in enhanced ozone transport into the subtropical latitudes (Baldwin et al. 2001; Weber et al. 2011; Lawrence et al. 2020; Plate 2.1x). Negative total ozone anomalies in the Southern Hemisphere extratropics are possibly related to the combination of the unusually long-lasting Antarctic ozone hole of 2020, extending into 2021, and the large ozone hole in the second half of 2021. The westerly phase of the QBO in late autumn of 2020 likely resulted in weaker ozone transport and higher polar ozone deficits in the Northern Hemispheric winter of 2021.

Figure 2.57 shows the long-term evolution of annual total column ozone for different zonal bands (near-global, NH, tropics, and SH), and for polar caps in March (for the NH cap) and October (for the SH cap). These are the months when polar ozone losses are usually at their maximum after a cold stratospheric winter in the respective hemispheres, which occurs every year in the SH ("ozone hole") but is more sporadic in the NH (see sections 6h and 5j, respectively). Total ozone shows above-average total ozone levels in 2021 in the outer tropical/subtropical region (Plate 2.1x). At middle latitudes, total ozone is at the lower range of the values from the last two decades (Figs. 2.57b,e; Plate 2.1x). Total ozone was near the minimum annual mean values observed during the entire 43-year satellite observation period in the SH extratropics and above Antarctica in October (Figs. 2.57d,e; see section 6h).

ODS-related total ozone changes since 1996 are on the order of +0.5% decade^{-1} in the extratropics of both hemispheres, but opposing long-term changes in atmospheric dynamics contributed to near-zero overall trends in the NH extratropics from 2000 to present (Coldewey-Egbers et al. 2022; Weber et al. 2022). Mean total ozone levels during the period 2017–20 are still 4% and 5% below the 1964–1980 mean in the extratropics of the NH and SH extratropics, respectively (Figs. 2.57b,d; Weber et al. 2022).

Figure 2.58 shows ozone time series at two altitudes in the lower (50 hPa/22 km altitude) and upper stratosphere (2 hPa/42 km altitude). The ozone evolution at both levels is broadly consistent with the projected range from various models of the Phase 1 Chemistry Climate Model Initiative (CCMI) using current scenarios of ODS and GHG changes (thick gray line in Fig. 2.57a and shaded area in Fig. 2.58; SPARC/IO3C/GAW 2019).

In 2021 SH extratropical lower stratospheric ozone was close to the lowest values seen in the last decade but higher than in 2020. The lower values are related to the above-average sizes of the Antarctic ozone holes in 2020 and 2021 (see section 6h).

The earliest and clearest sign of ODS-related ozone recovery was detected in the upper stratosphere, where dynamic variability plays a lesser role (e.g., Newchurch et al. 2003; Godin-Beekmann

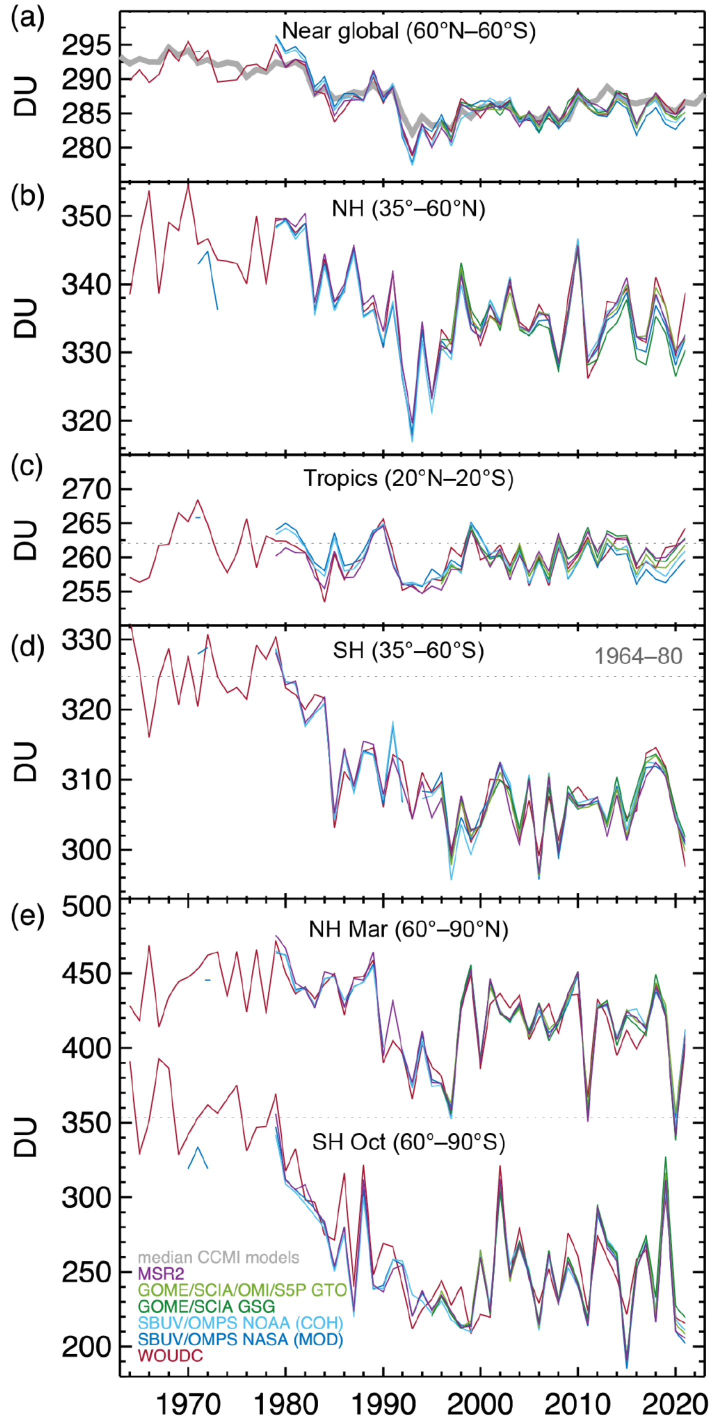

Fig. 2.57. Time series of annual mean total column ozone (DU) for (a) global (60°S–60°N), (b) NH (35°–60°N), (c) tropics (20°S–20°N), and (d) SH (35°–60°S); and (e) polar (60°–90°) total column ozone in Mar (NH) and Oct (SH), the months when polar ozone losses usually are largest. Data are from WOUDC (World Ozone and Ultraviolet Radiation Data Centre) ground-based measurements combining Brewer, Dobson, SAOZ (Système D'Analyse par Observations Zénithales), and filter spectrometer data (red: Fioletov et al. 2002, 2008); the BUV/SBUV/SBUV2/OMPS merged products from NASA (V8.7. dark blue, Frith et al. 2014, 2017), and NOAA (V8.8, light blue: J. D. Wild and L. M. Ciasto, person. comm. 2019); the GOME/SCIAMACHY/GOME-2 products GSG from University of Bremen (dark green, Weber et al. 2022), and GTO from ESA/DLR (light green, Coldewey-Egbers et al. 2015; Garane et al. 2018). MSR-2 (purple) assimilates nearly all ozone datasets after corrections based on the ground-based data (van der A et al. 2015). All datasets have been bias-corrected by subtracting averages for the reference period 1998–2008 and adding back the mean of these averages. The dotted gray lines in each panel show the average ozone level for 1964–80 calculated from the WOUDC data. The thick gray line (panel a) shows the median from chemistry-climate (CCMI)-1 ref C2 model runs (SPARC/IO3C/GAW 2019). Most of the observational data for 2021 are preliminary.

et al. 2022). Upper stratospheric ozone has shown an increase of about +2% $decade^{-1}$ since the late 1990s (e.g., Steinbrecht et al. 2017; Arosio et al. 2019; Szelag et al. 2020; Sofieva et al. 2021; Godin-Beekmann et al. 2022). In general, ozone observations in the lower stratosphere suggest little change or even a continuing decline over the last two decades (Fig. 2.58; Ball et al. 2018, 2020; Chipperfield et al. 2018; Wargan et al. 2018; Godin-Beekmann et al. 2022).

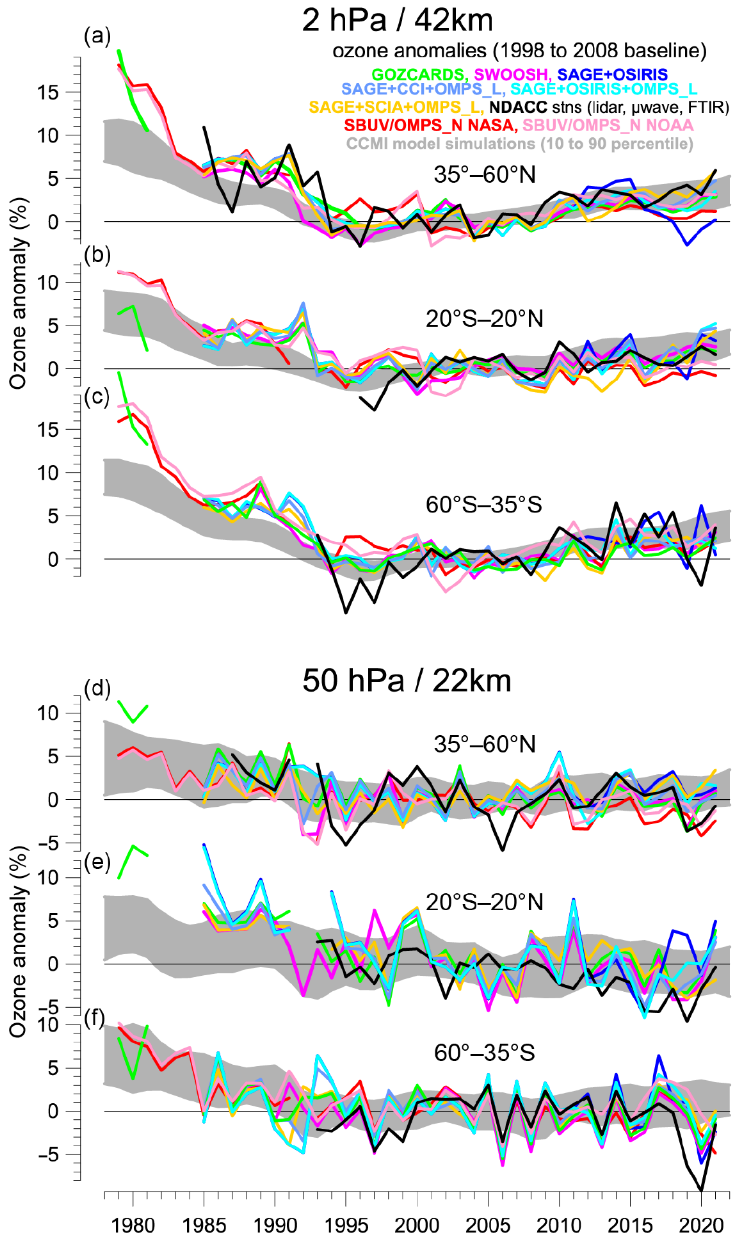

Fig. 2.58. Annual mean anomalies of ozone (%) in (a–c) the upper stratosphere near 42-km altitude or 2-hPa pressure and (d–f) in the lower stratosphere, near 22 km or 50 hPa for the NH (35°–60°N; a,d), tropics (20°S–20°N; b,e), and SH (35°–60°S; c,f), respectively. Anomalies are GOZCARDS referenced to the 1998–2008 baseline. Colored lines are long-term records obtained by merging different limb (SWOOSH, SAGE+OSIRIS, SAGE+CCI+OMPS-L, SAGE+SCIAMACHY+OMPS-L) or nadir-viewing (SBUV, OMPS-N) satellite instruments. The nadir-viewing instruments have much coarser altitude resolution than the limb-viewing instruments. This can cause differences in some years, especially at 50 hPa. The black line is from merging ground-based ozone records at seven NDACC stations employing differential absorption lidars and microwave radiometers. See Steinbrecht et al. (2017), WMO (2018), and Arosio et al. (2018) for details on the various datasets. Gray shaded area shows the range of chemistry–climate model simulations from CCMI-1 refC2 (SPARC/IO3C/GAW, 2019). Ozone data for 2021 are not yet complete for all instruments and are still preliminary.