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Variability of temperature and ozone in the upper troposphere and lower stratosphere from multi-satellite observations and reanalysis data

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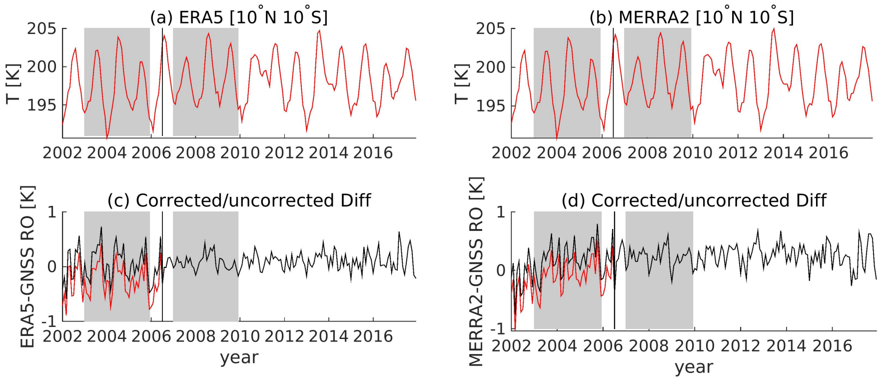

Figure S1: Illustration of the ERA5 and MERRA2 bias correction using the GNSS RO as a transfer function. Plotted are temperature time series of ERA5 (a) and MERRA2 (b) and their differences with GNSS RO (c and d) at 70 hPa averaged between 10°S and 10°N. Uncorrected and bias corrected values are shown in red and black lines, respectively. The shaded areas mark the periods of averaging and the vertical lines indicate the changes in reanalyses. The average differences between the uncorrected temperature and GNSS RO are shown in blue.

For each discontinuity, the monthly differences (reanalysis minus GNSS RO) were first calculated at every latitude and level and averaged over three years before Δ_1 and three years after the discontinuity Δ_2. The reanalyses were then bias corrected by subtracting the difference $\Delta_2 - \Delta_1$ in the period 2002-2006.

The signal to noise ratio is estimated based on three 145-years CESM simulations. The CESM runs were integrated in a fully coupled mode with an interactive ocean for the time period 1955 to 2099. All anthropogenic forcing, e.g. GHGs and ODSs were fixed to values at the year 1960. The three simulations are slightly different with the natural forcing. The first run used observed solar irradiance, time varying volcanic aerosols and a nudged QBO, while the second run fixed the solar irradiance as a constant and the third run did not include a QBO. The influences of solar cycle, volcanic aerosols and QBO were excluded by a multiple linear regression before the calculations of the background noise.

To assess the effect of seasonal and interannual variability on 16-year temperature trends, we fit linear trends to overlapping 192-month segments of the 1740-month in each of CESM runs. For maximally overlapping 192-month intervals (i.e., for overlap by all but one month), one simulation yields 1549 samples of 192-month trends. Following the method described by Bandoro et al. (2017) and Santer et al. (2011), we exclude the largest cooling or warming trends from our analysis and calculate the standard deviations of the 16-year trends. The signal to noise ratio is then estimated using the calculated trends (signal) divided by the standard deviations of the 16-year trends (noise).

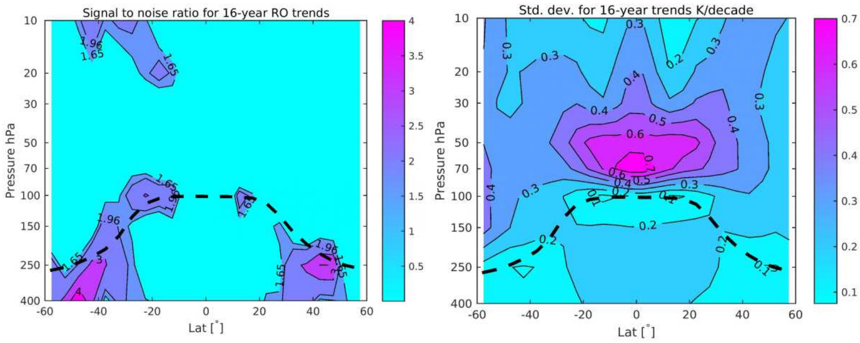

Figure S2: Signal to noise ratios (links) are estimated RO trends divided by the standard deviations of model trends (right), calculated using overlapping time series segment. The signal to noise study based on a 145-years WACCM simulations for the time period 1955 to 2099.

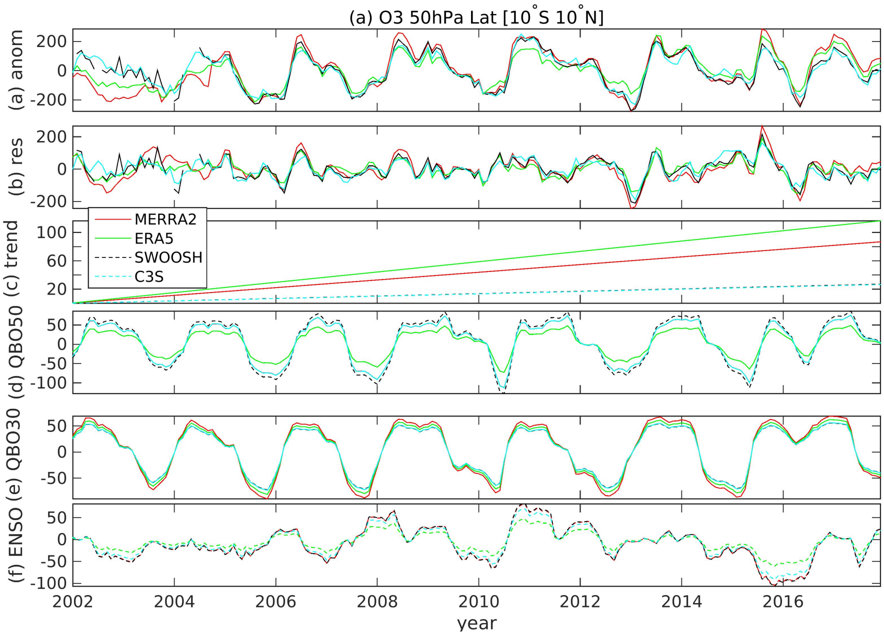

Figure S3: Ozone anomaly at pressure level 50 hPa (a) with latitude bands TP(10°S-10°N); ERA5 (green), C3S (light blue), MERRA2 (red) and SWOOSH (black) are included; (b) The corresponding residual; (c) The linear terms; (d) The QBO50 terms; (e) The QBO30 terms and (f) the ENSO terms; The solid lines in (c-f) marked the significant terms and the dash lines in (c-f) marked the insignifcant terms.

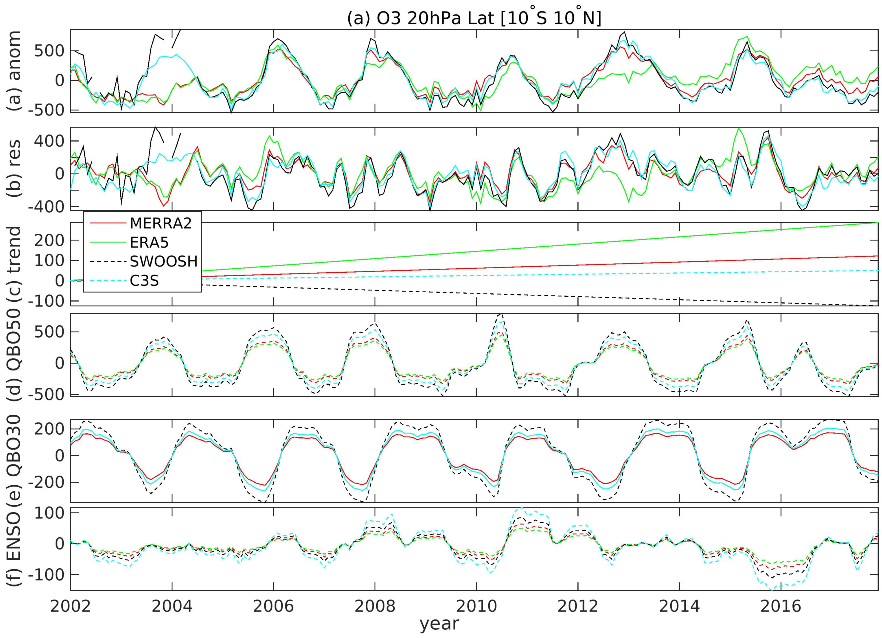

Figure S4: Same as figure S3 but for 20 hPa.

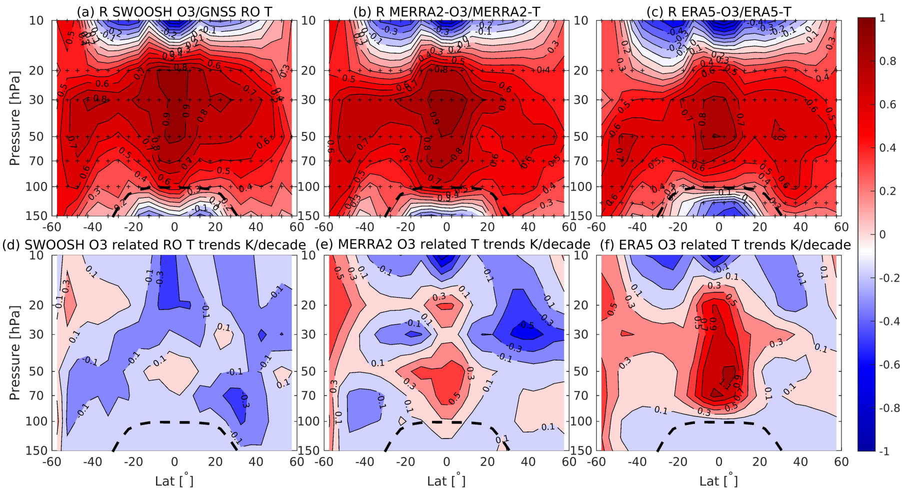

Figure S5: Correlation coefficient between GNSS temperature and SWOOSH ozone(a); MERRA2 temperature and ozone (b);ERA5 temperature and ozone (c); The '+' marked trends found to be more than 95% statistically significant. (d) SWOOSH ozone related GNSS RO temeprature trends in K/decade; (e) MERRA2 ozone related temperature trends in K/decade; (f) ERA5 ozone related temperature trends in K/decade.

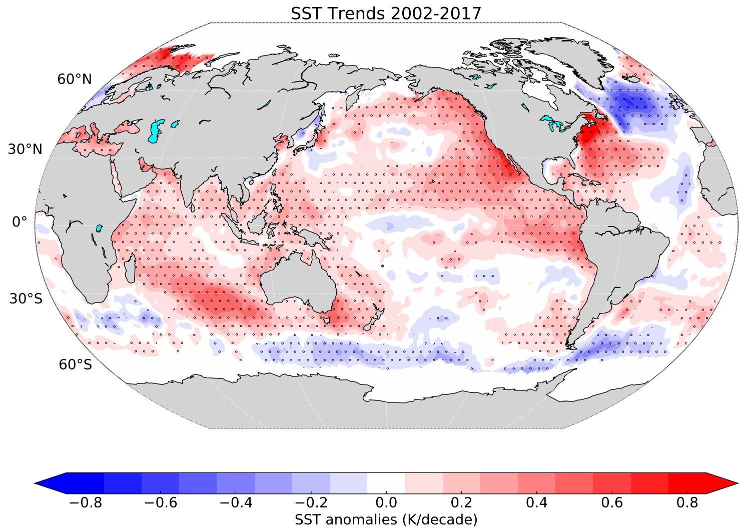

Figure S6: Global distribution of SST trends for the period 2002-2017 based on HadISST. The black dots marked the significant area at 95% level.