Phase unlocking and the modulation of tropopause-level trace gas advection by the quasibiennial oscillation

Kasturi Shah¹, Susan Solomon¹, Douglas Kinnison², Qiang Fu³, David WJ Thompson⁴

¹ Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
² Atmospheric Chemistry Observations and Modeling, National Center for Atmospheric Research, Boulder, CO 80307, USA
³ Department of Atmospheric Sciences, University of Washington, Seattle, WA 98195, USA
⁴ Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, USA

Supplemental figures and movie

Figure S1 – Removing the long-term increases from AGAGE tracer concentrations at the surface. (a) Global mean data for N₂O (blue) overlaid by a piece-wise linear fit (black) with breakpoints in 1988, 1991, 1994, 2002 and 2012. CFC-11 (orange) is overlaid with a piecewise linear fit with breakpoints in 1989, 1991, 1993, 1995, 2002 and 2011. (b) The detrended AGAGE concentrations for N₂O and CFC-11.
Figure S2 Same as Figure 2, but for interannual anomalies of the CFC-11 advection terms.
Figure S3 Same as Figure 4 but for calculations of interannual anomalies of \( A_y + A_o \) of CFC-11 from WACCM.
**Figure S4** Same as Figure 5 but for interannual anomaly calculations of $A_y + A_z$ of CFC-11 from WACCM, for calculations of $A_y + A_z$ of CFC-11 from ACE measurements and JRA-55 reanalysis, and for CFC-11 global-mean near-surface concentrations from AGAGE. The number of total counts in each quantile for model ensemble/ACE-JRA55 results/AGAGE are: (a) 300/15/35 (b) 300/11/35 (c) 300/15 (d) 300/11.
Figure S5 Seasonal partitioning of QBO phases of the WACCM ten-member ensemble (blue) and JRA55 (red). The westerly QBO is defined as the 0.75 quantile and the easterly QBO is defined as the 0.25 quantile of $u$ at 50 hPa.
Figure S6 Same as Figure 7 but for interannual anomalies of $A_y + A_z$ for N$_2$O at 350K in the Southern Hemisphere.

**Supplementary Movie 1**

Month-by-month video of the WACCM ensemble-mean interannual anomalies of (a) zonal-mean temperature, (b) zonal-mean zonal wind, (c) zonal-mean N$_2$O as colour contours and $<A_y,A_z>$ as arrows, (d) zonal-mean CFC-11 as colour contours and $<A_y,A_z>$ as arrows. In each panel, the isentropes are shown as thin blue contours and the climatological tropopause as a thick black line.