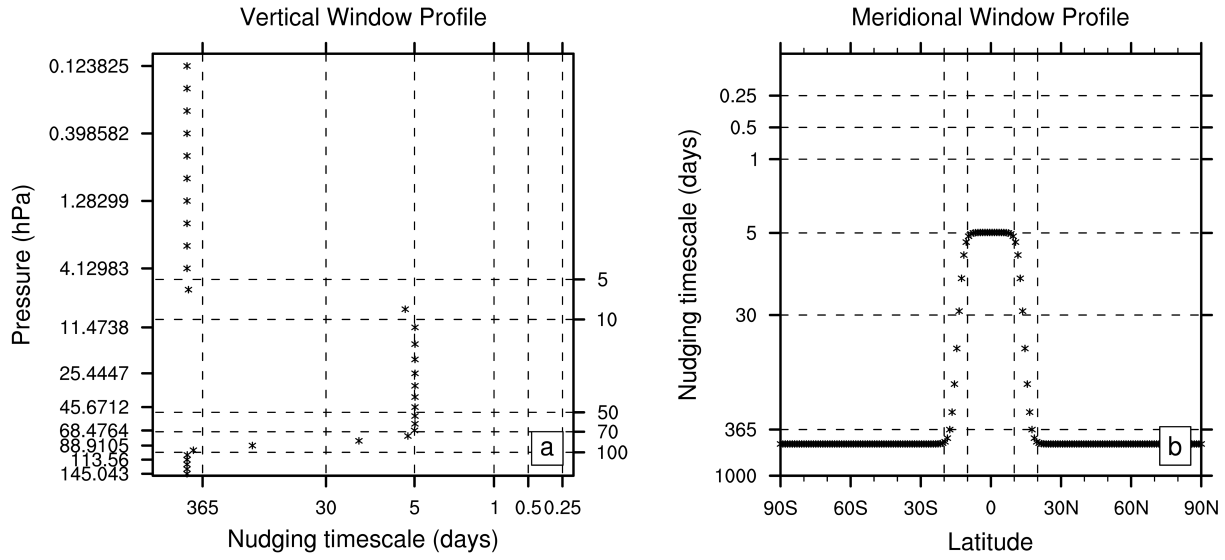
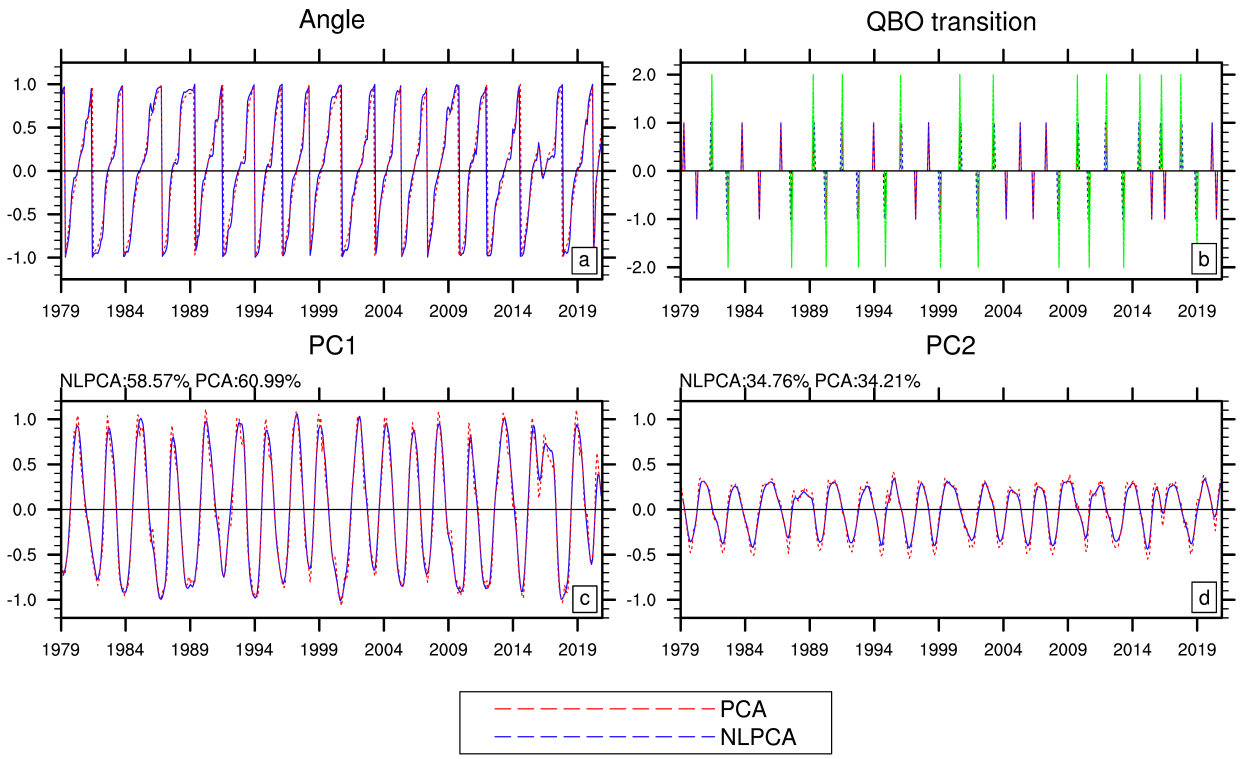
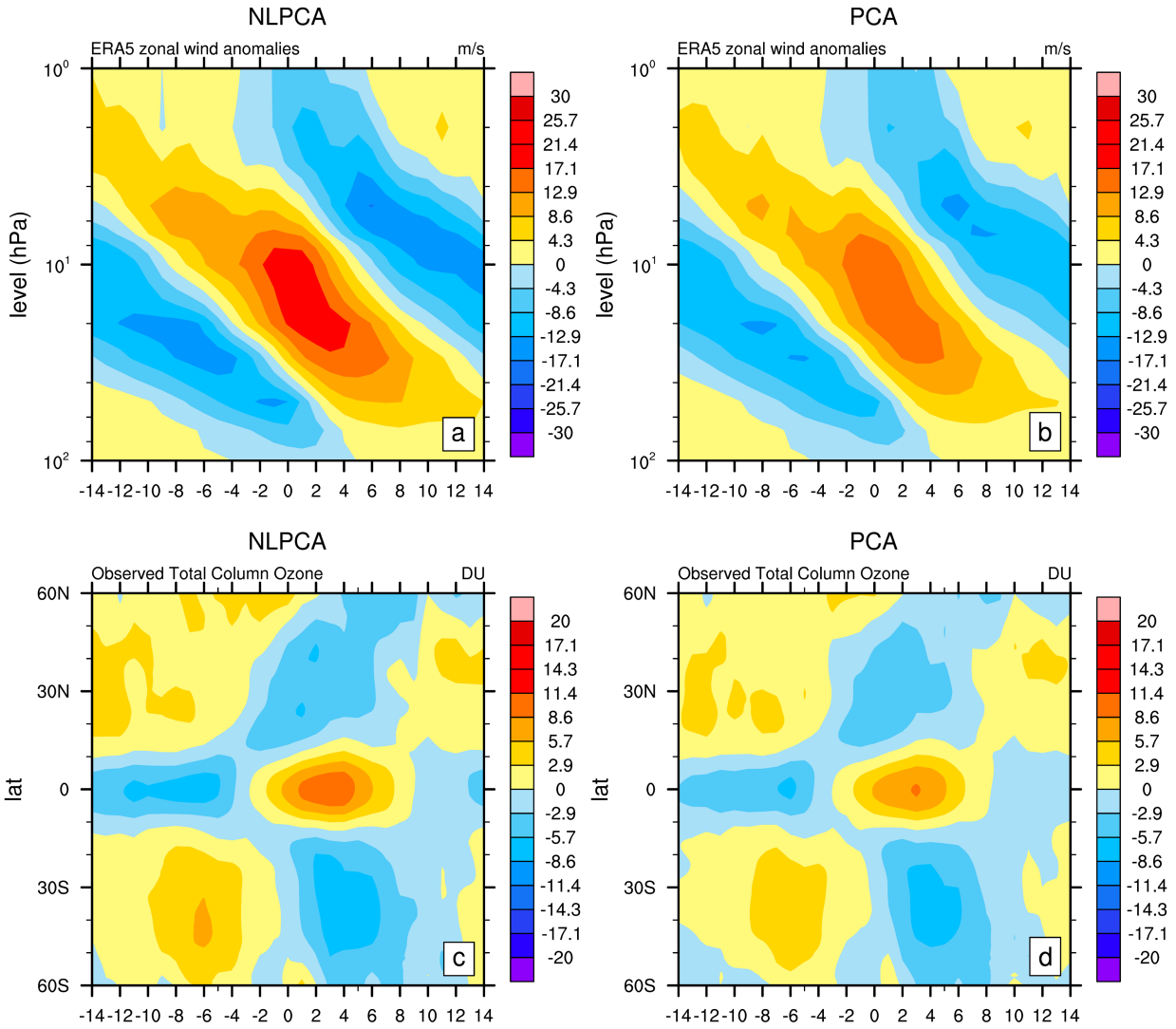


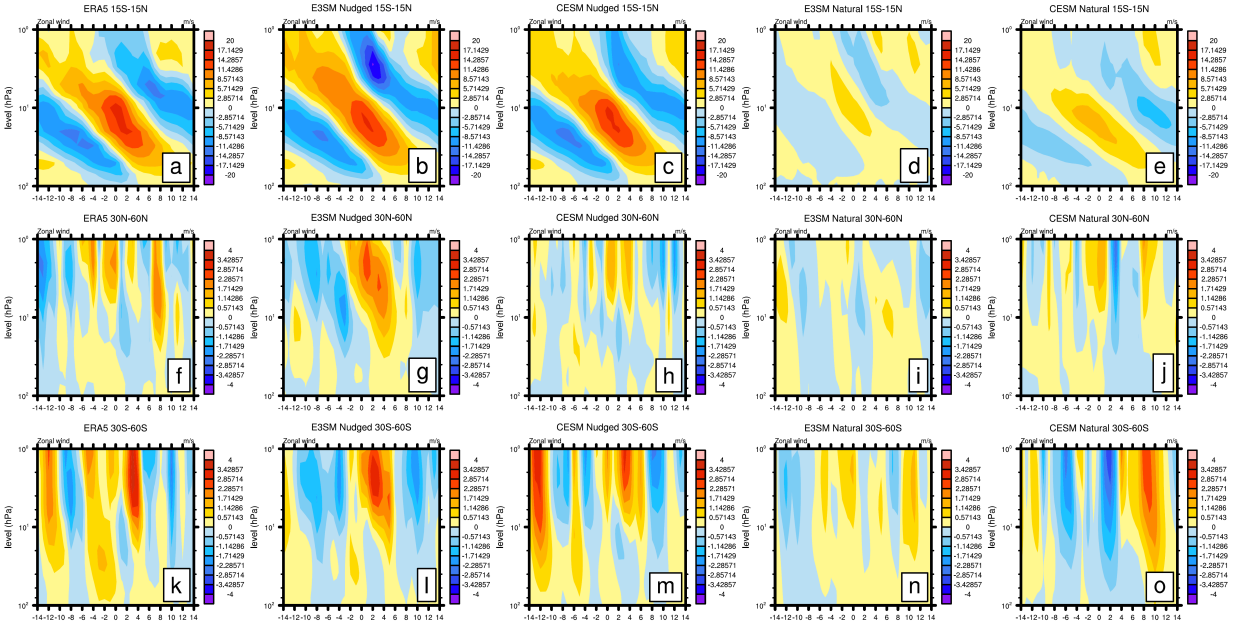
Supplementary Figure 1 Spatial dependence of nudging timescale in the (a) vertical and (b) meridional directions for E3SMv2.



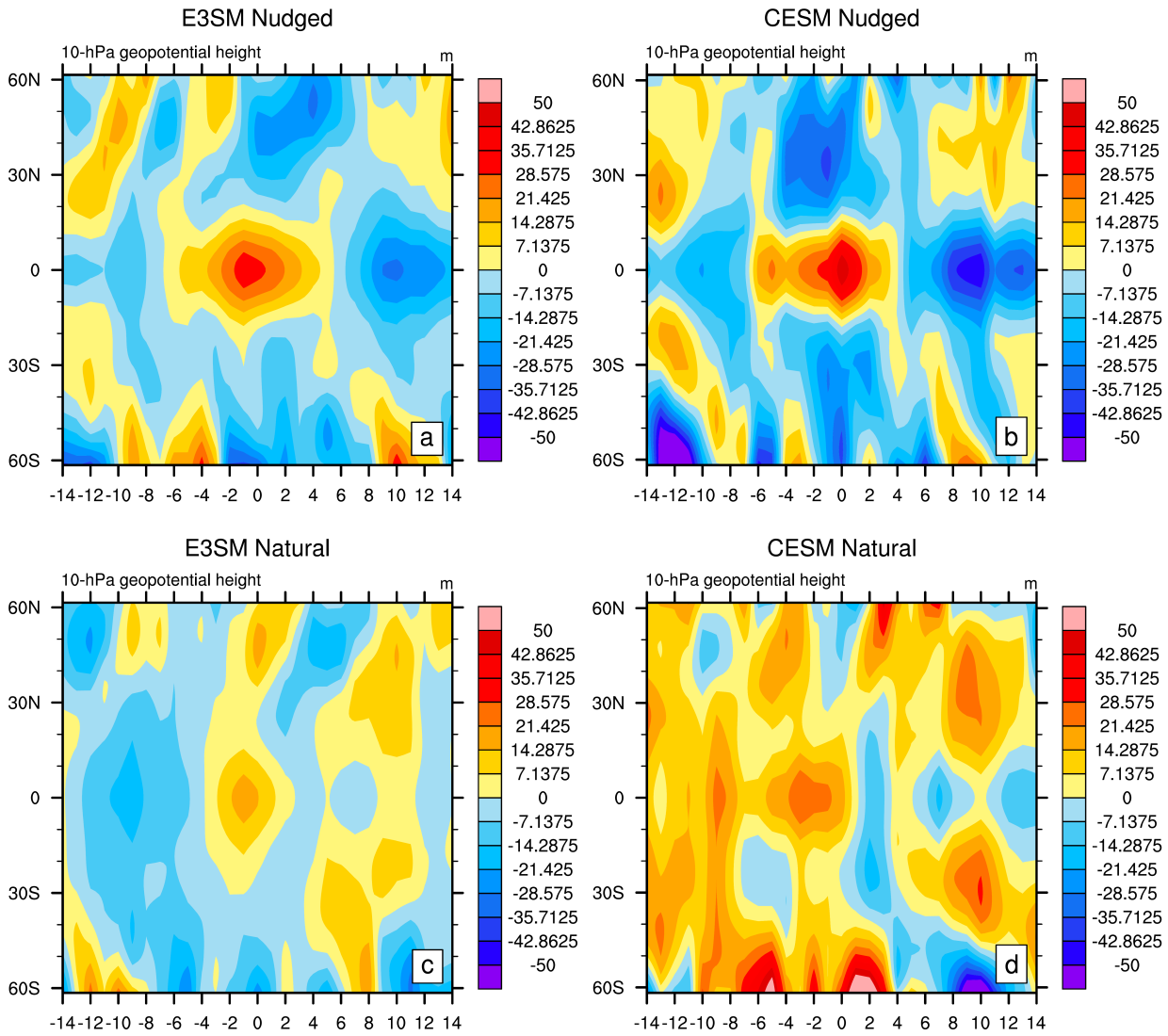
Supplementary Figure 2 (a) normalized QBO phase angle derived from NLPCA/PCA (red/blue), and (b) NLPCA/PCA representation of the QBO phase transition (1 denotes QBOw->QBOe, -1 denotes QBOe->QBOw, green denotes regions where NLPCA/PCA-derived QBO transition is different), (c) mode 1 and (d) mode 2 principal component. The angle is normalized by π, and 0 and 1 indicate QBO phase transitions (QBOe -> QBOw or QBOw -> QBOe). For showing purpose, PCA1 and PCA2 are divided by 1500 and 1000, respectively.



Supplementary Figure 3 ERA5 tropical zonal wind anomalies (15S-15N, m/s) for 1979-2020 and observed total column ozone (DU) as a function of QBO phase based on index derived from (a, c) NLPCA, (b, d) PCA.



Supplementary Figure 4 Pressure-time cross-section of the Extratropic (30S-60S/30N-60N) 1979-2020 anomalous zonal wind (m/s) for (a, f, k) ERA5, (b, g, l) E3SMv2 Nudged, (c, QBOe, m) CESM Nudged, (d, i, n) E3SMv2 Natural, (e, j, o) CESM2 Natural. 0 is centered on the month when QBO transits from QBOe to QBOw (determined by when current QBO index<0 and next QBO index>0). The QBO phase is determined by 5S-5N average of the zonal wind.



Supplementary Figure 5 10-hPa geopotential height (m) for (a) E3SMv2 Nudged, (b) CESM2 Nudged, (c) E3SMv2 Natural, (d) CESM2 Natural. 0 is centered on the month when QBO transits from QBOe to QBOw (determined by when current QBO index<0 and next QBO index>0). The QBO phase is determined by 5S-5N average of the zonal wind.