

The Supplementary Information of

**The Disappearing Quasi-Biennial Oscillation under
Sustained Global Warming**

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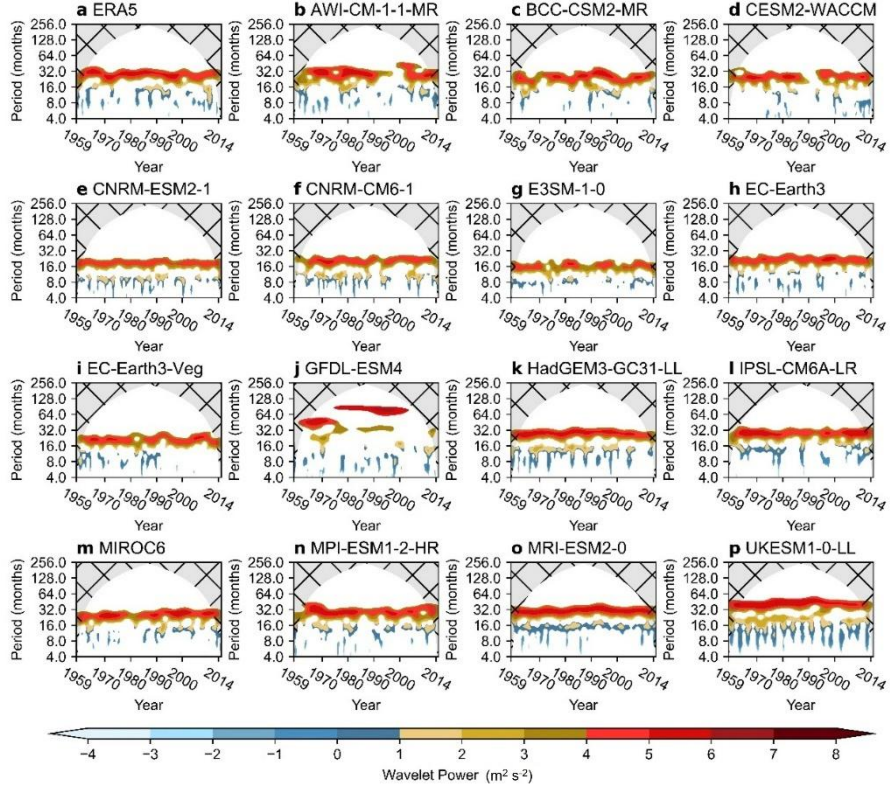
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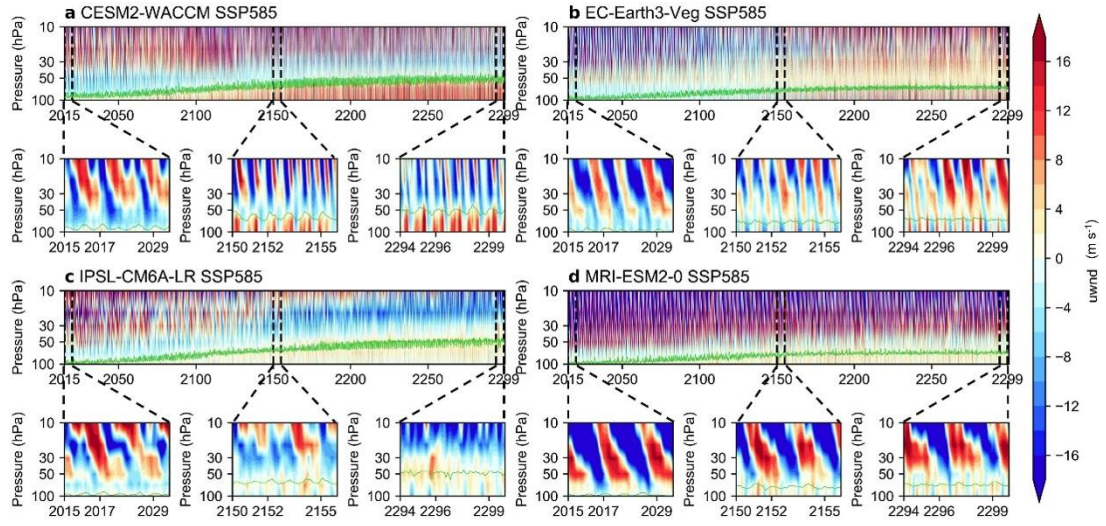
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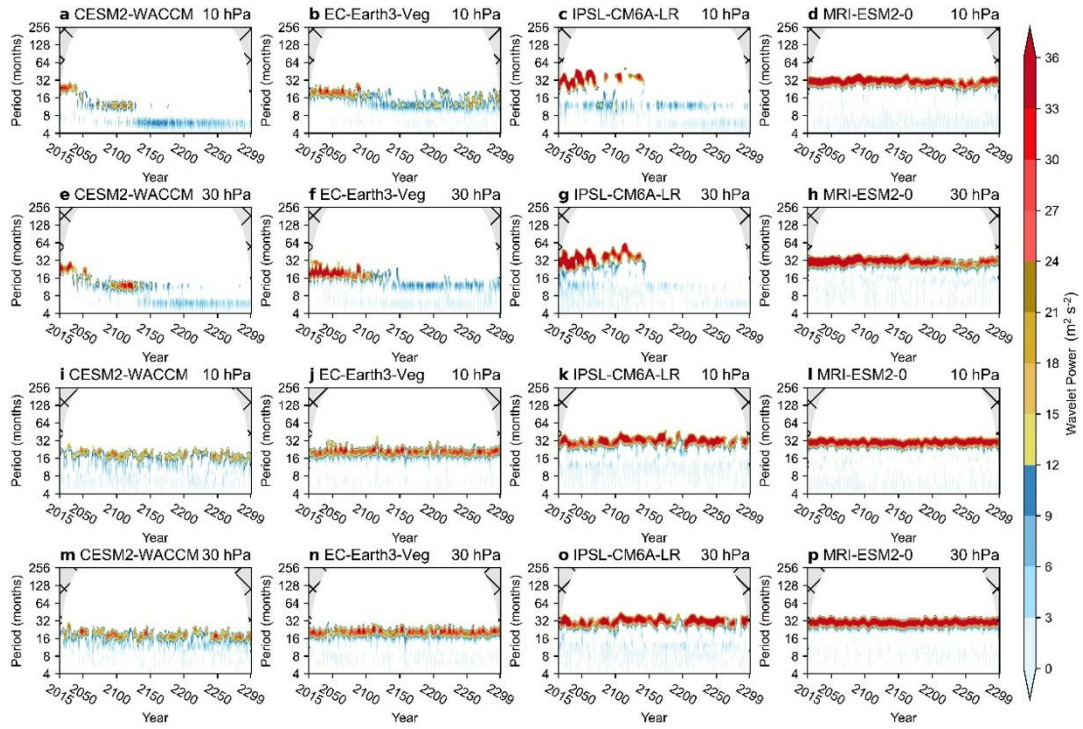
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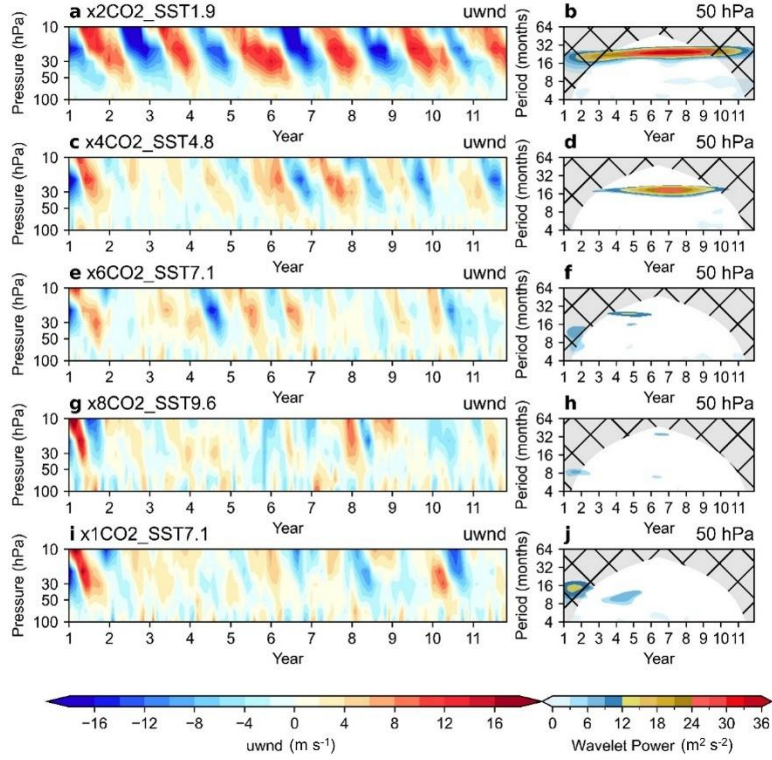
Supplementary Fig. 1: Changes in the quasi-biennial oscillation (QBO) period based on observational data and model simulations. a–p The wavelet analysis results for the 50 hPa tropical region (5°S – 5°N , 0° – 360°) zonal-mean zonal wind from ERA5 data and model simulations. The filled color indicates wavelet power passing the 95% confidence level chi-square test.



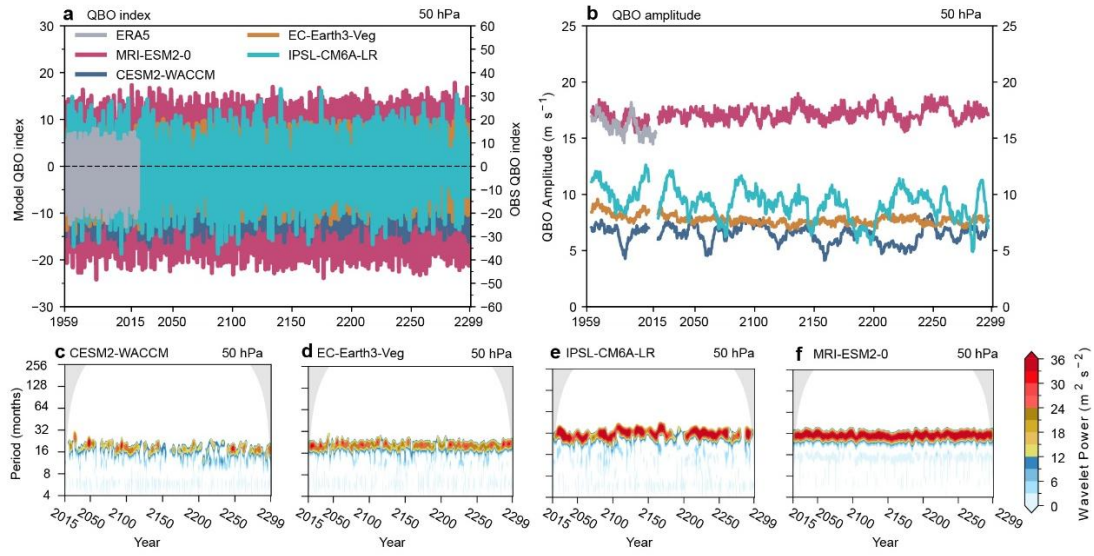
Supplementary Fig. 2: Height–time evolution of tropical zonal-mean zonal wind under the SSP5-8.5 scenario. **a–d** Results from the CESM2-WACCM, EC-Earth3-Veg, IPSL-CM6A-LR, and MRI-ESM2-0 models, respectively, averaged over the tropical region (0° – 360° , 5°S – 5°N). Dashed black lines indicate selected periods for detailed analysis. Enlarged panels below each model plot display the corresponding zonal wind evolution during these periods. The bright green line represents the tropical tropopause.



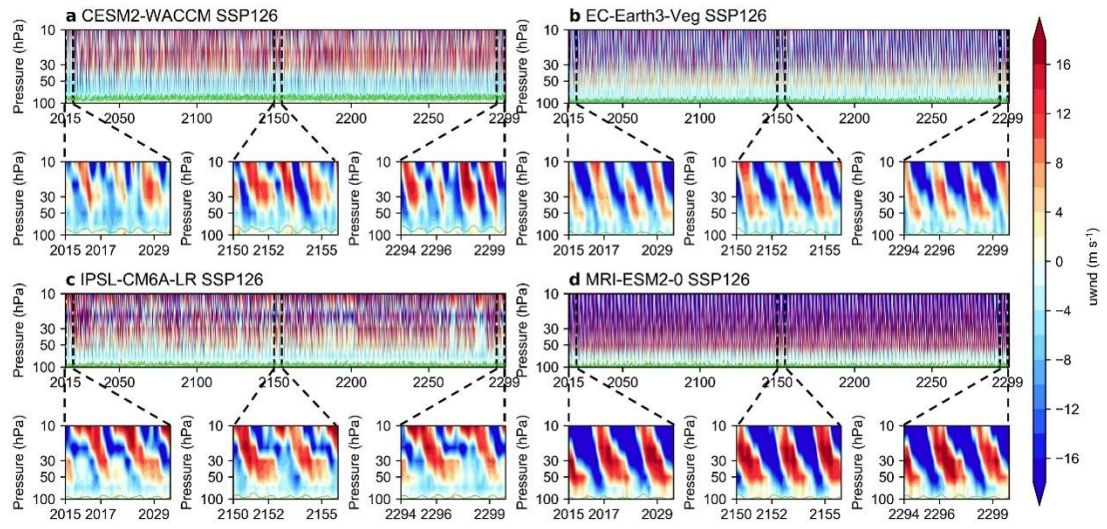
Supplementary Fig. 3: Wavelet analysis of quasi-biennial oscillation (QBO) indices at 10 hPa and 30 hPa under SSP5-8.5 and SSP1-2.6 scenarios. a–h Results under the SSP5-8.5 scenario. **i–p** Results under SSP1-2.6. **a–d** and **i–l** correspond to 10 hPa, while **e–h** and **m–p** correspond to 30 hPa. Each subplot is labeled with the respective model’s name. Filled contours indicate wavelet power significant at the 95% confidence level based on a chi-square test.



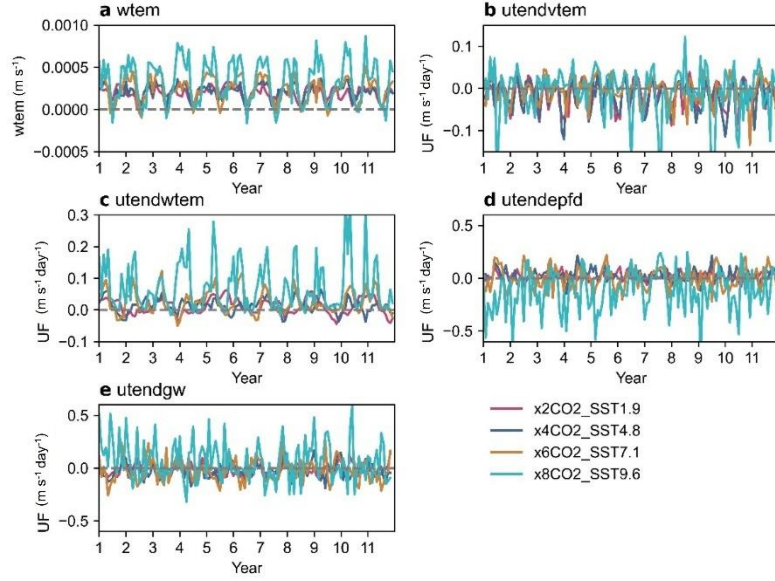
Supplementary Fig. 4: Height–time evolution of deseasonalized tropical zonal-mean zonal wind (0° – 360° , 5°S – 5°N) and wavelet power spectra of the 50 hPa quasi-biennial oscillation (QBO) index from CO_2 -doubling sensitivity experiments. Left column (top to bottom): simulations under $2\times$, $4\times$, $6\times$, and $8\times$ preindustrial CO_2 concentrations, and a sixth experiment with SSTs corresponding to the $6\times$ CO_2 case but with CO_2 reset to preindustrial levels (see Methods). Right column: corresponding wavelet analyses of the deseasonalized 50 hPa QBO index for each experiment.



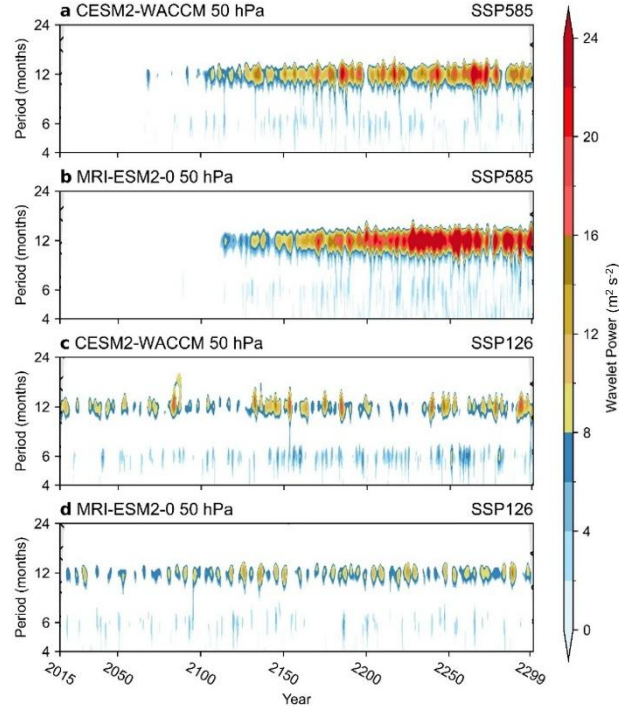
Supplementary Fig. 5: Same as Fig 1, but for the SSP1-2.6 scenario.



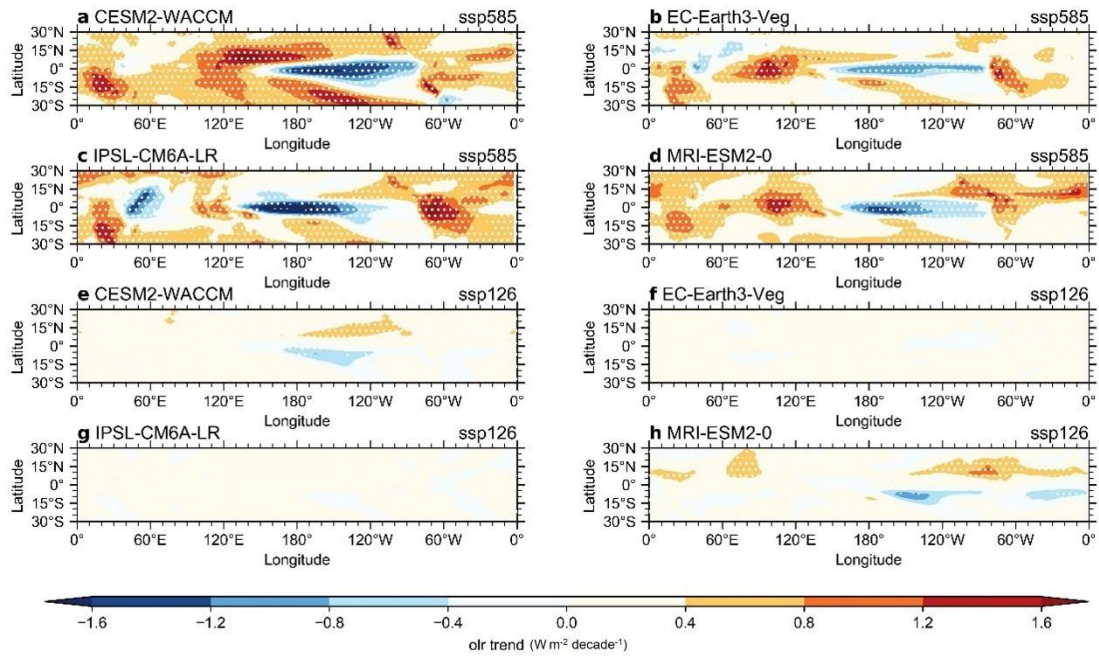
Supplementary Fig. 6: Same as Supplementary Fig. 2, but for the SSP1-2.6 scenario.



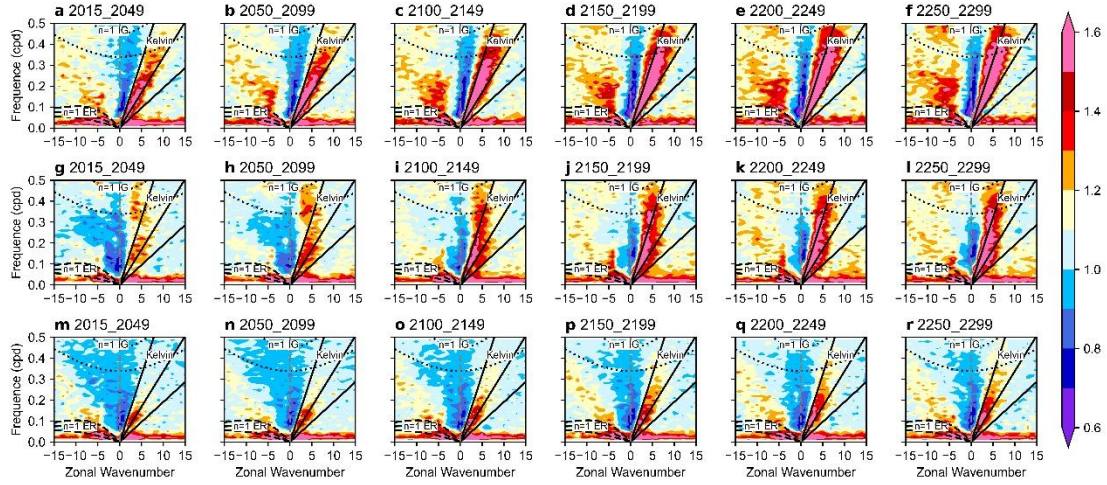
Supplementary Fig. 7: Momentum budget analysis and residual vertical velocity at 50 hPa from CESM2-WACCM simulations under 2×, 4×, 6×, and 8× CO₂ concentrations. **a** The changes in residual vertical velocity. **b–e** The zonal wind forcing due to meridional advection, vertical advection, resolved waves and gravity wave forcing, respectively. Coloured lines denote simulations with different CO₂ concentrations (see Methods): magenta indicates 2× CO₂ (x2CO2_SST1.9), blue indicates 4× CO₂ (x4CO2_SST4.8), orange indicates 6× CO₂ (x6CO2_SST7.1), and cyan indicates 8× CO₂ (x8CO2_SST9.6).



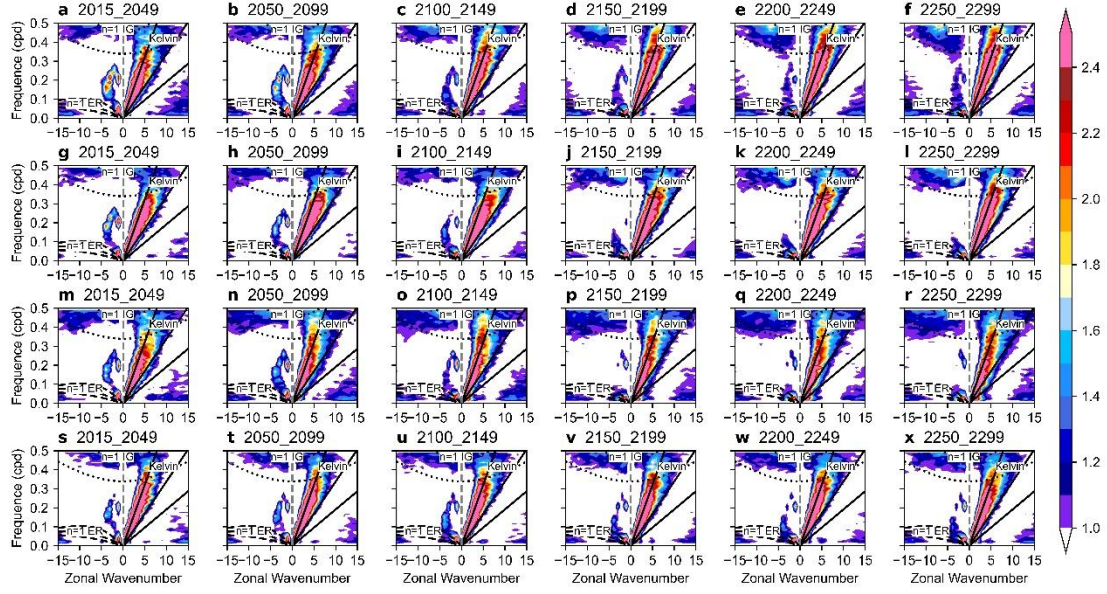
Supplementary Fig. 8: Wavelet analysis of the residual vertical velocity at 50 hPa in the tropical region (5°S–5°N, 0°–360°). **a, b** Results under the SSP5-8.5 scenario. **c, d** Results under the SSP1-2.6 scenario. The filled colours denote wavelet power that passes the 95% confidence level according to the chi-square test.



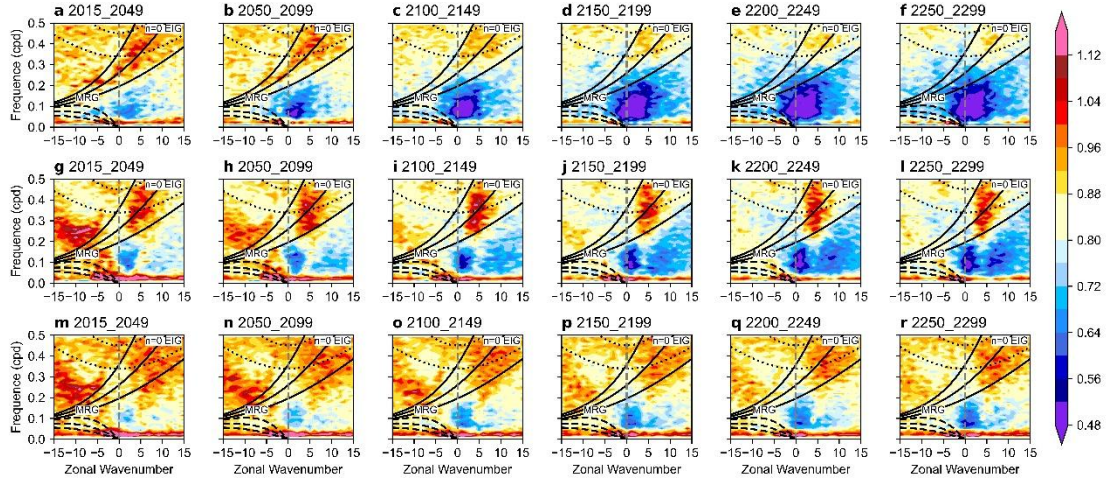
Supplementary Fig. 9: Trends in outgoing longwave radiation (OLR) over the tropical region under SSP5-8.5 and SSP1-2.6 scenarios. a–d. Results from the SSP5-8.5 scenario. e–h Results from the SSP1-2.6 scenario. The shading shows the linear trends. Stippling denotes regions where the trends are statistically significant at the 95% confidence level based on a two-tailed t-test.



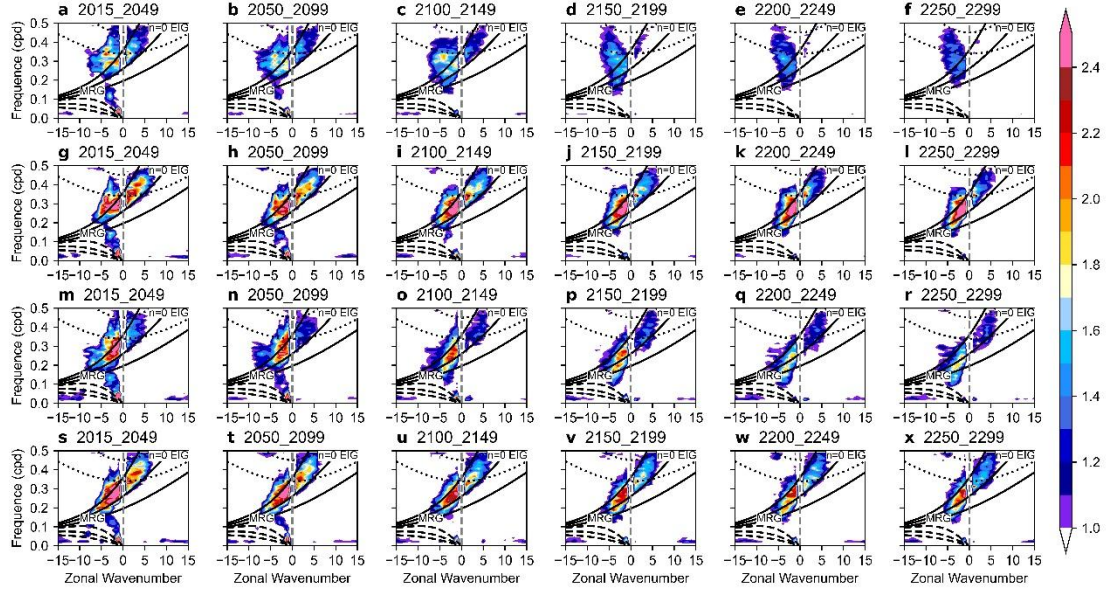
Supplementary Fig. 10: The symmetric component of the tropical waves (15°S–15°N) extracted by regions of wavenumber-frequency filtering based on the outgoing longwave radiation (OLR) under the SSP5-8.5 scenario. a–f Results from CESM2-WACCM. **g–l** Results from IPSL-CM6A-LR. **m–r** Results from MRI-ESM2-0. Results for EC-Earth3-Veg are not shown due to the unavailability of daily OLR data in the ESGF database. Columns represent different time periods, with the corresponding years indicated in the upper right of each panel. Black curves indicate the theoretical dispersion relations for equatorial wave modes, including Kelvin waves, equatorial Rossby waves ($n = 1$ ER), and inertia-gravity waves ($n = 1$ IG). The labelled regions highlight the dominant wave types in the corresponding wavenumber-frequency ranges. The filtering method is described in the Methods section.



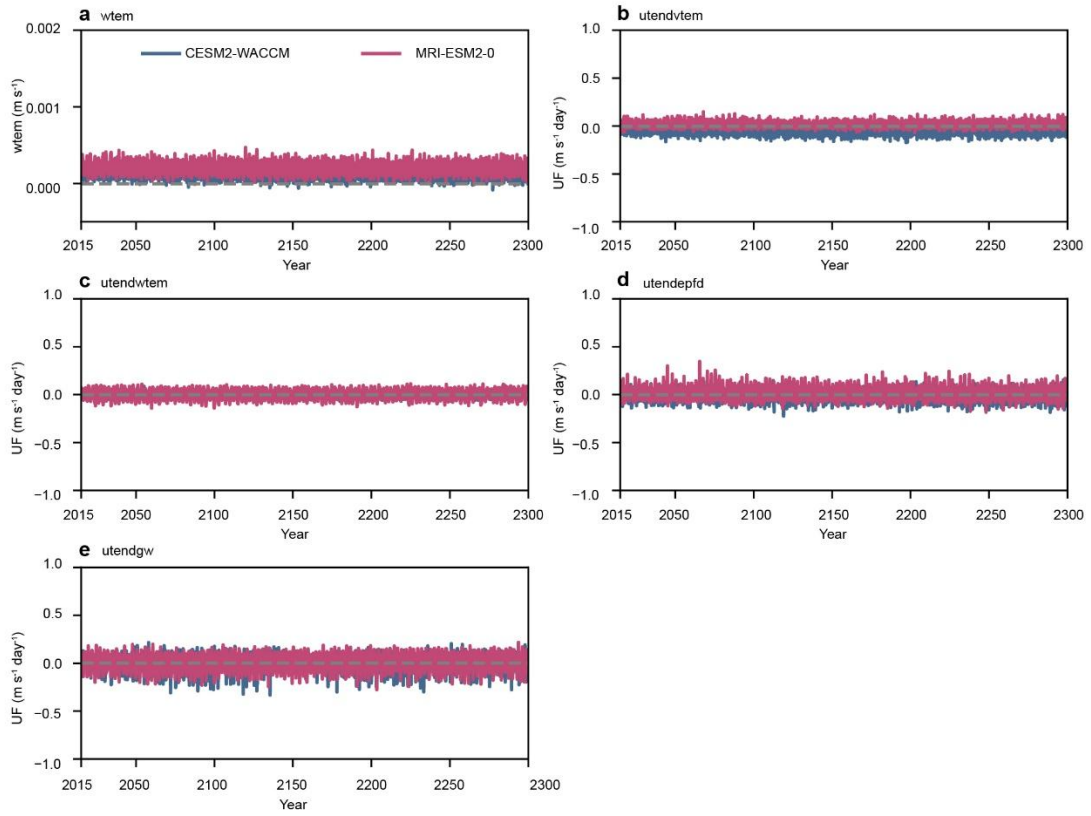
Supplementary Fig. 11: Power spectral density of symmetric modes of zonal wind perturbations at 50 hPa under the SSP5-8.5 scenario. Power spectra are computed using wavenumber-frequency filtering (see Methods), based on zonal wind perturbations averaged over 15°N–15°S. Columns represent different time periods, with the corresponding years indicated in the upper right corner of each panel. Rows correspond to results from CESM2-WACCM (a–f), EC-Earth3-Veg (g–l), IPSL-CM6A-LR (m–r), and MRI-ESM2-0 (s–x), respectively. Black curves indicate the theoretical dispersion relations for equatorial wave modes, including Kelvin waves, equatorial Rossby waves ($n = 1$ ER), and inertia-gravity waves ($n = 1$ IG). The labelled regions highlight the dominant wave types in the corresponding wavenumber-frequency ranges. The filtering method is described in the Methods section.



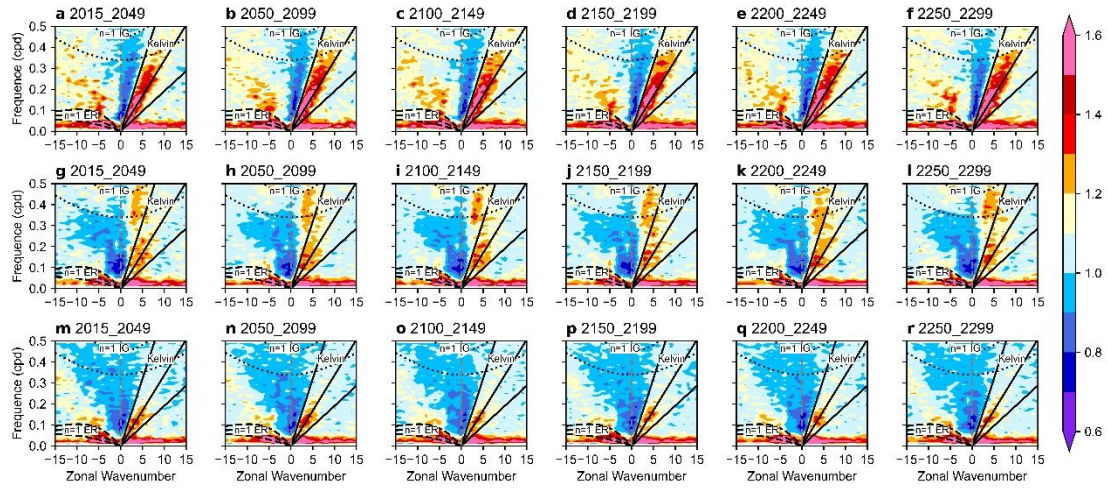
Supplementary Fig. 12: The antisymmetric component of the tropical waves (15°S–15°N) extracted by regions of wavenumber-frequency filtering based on the outgoing longwave radiation (OLR) under the SSP5-8.5 scenario. a–f Results from CESM2-WACCM. g–l Results from IPSL-CM6A-LR. m–r Results from MRI-ESM2-0. Results for EC-Earth3-Veg are not shown due to the unavailability of daily OLR data in the ESGF database. Columns represent different time periods, with the corresponding years indicated in the upper right of each panel. Black curves show the theoretical dispersion relations for equatorial wave modes, including mixed Rossby-gravity (MRG) waves and eastward inertia-gravity waves ($n = 0$ EIG). The labelled regions highlight the dominant wave types in the corresponding wavenumber-frequency ranges. The filtering method is described in the Methods section.



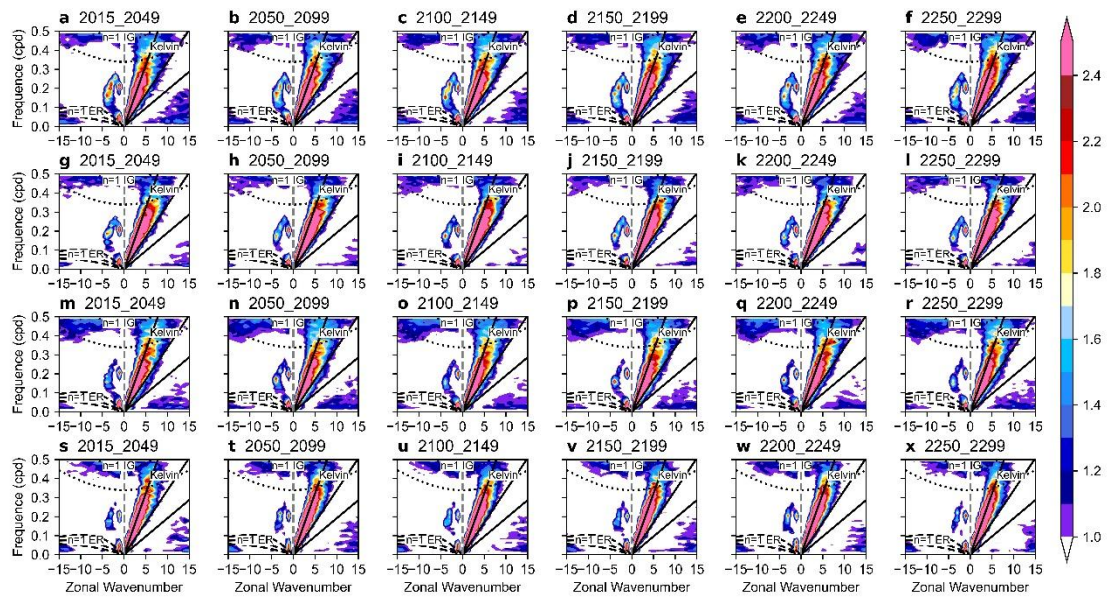
Supplementary Fig. 13: Power spectral density of antisymmetric modes of zonal wind perturbations at 50 hPa under the SSP5-8.5 scenario. Power spectra are computed using wavenumber–frequency filtering (see Methods), based on zonal wind perturbations averaged over 15°N–15°S. Columns represent different time periods, with the corresponding years indicated in the upper right corner of each panel. Rows correspond to results from CESM2-WACCM (a–f), EC-Earth3-Veg (g–l), IPSL-CM6A-LR (m–r), and MRI-ESM2-0 (s–x), respectively. Black curves show the theoretical dispersion relations for equatorial wave modes, including mixed Rossby-gravity (MRG) waves and eastward inertia-gravity waves ($n = 0$ EIG). The labelled regions highlight the dominant wave types in the corresponding wavenumber-frequency ranges. The filtering method is described in the Methods section.



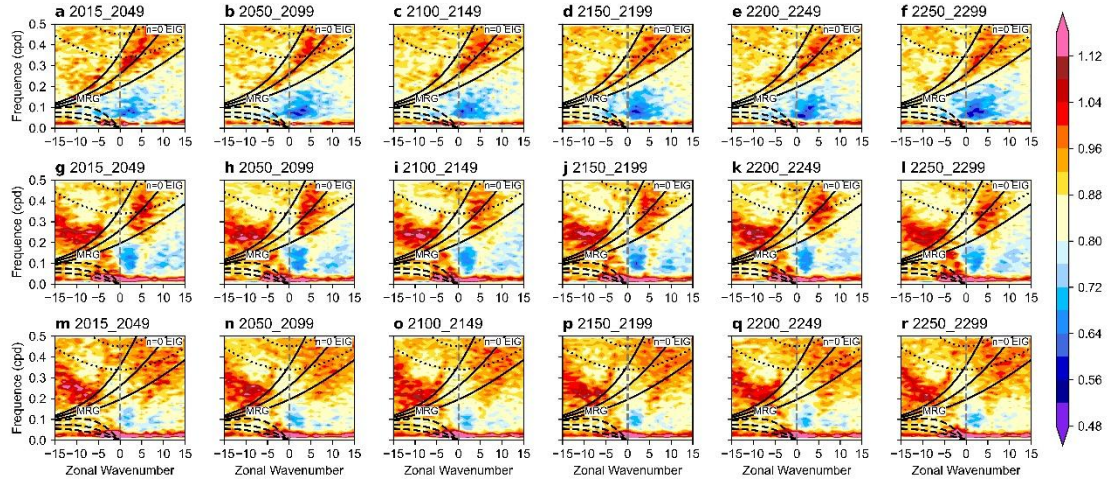
Supplementary Fig. 14: Same as Fig. 2a–e, but for the SSP1-2.6 scenario.



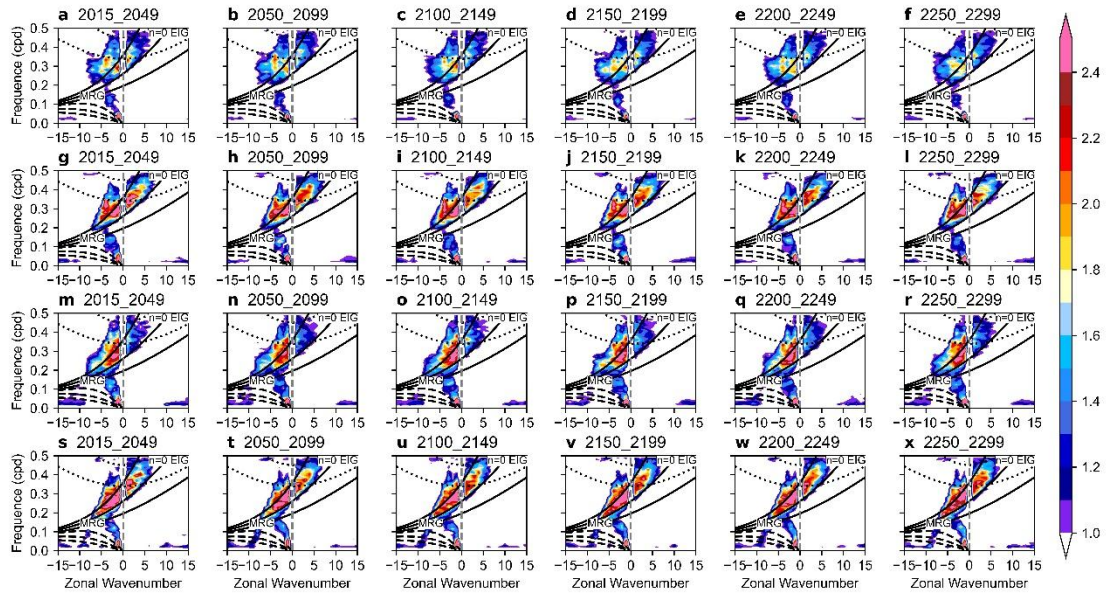
Supplementary Fig. 15: Same as Supplementary Fig. 10, but for the SSP1-2.6 scenario.



Supplementary Fig. 16: Same as Supplementary Fig. 11, but for the SSP1-2.6 scenario.



Supplementary Fig. 17: Same as Fig.S12, but for the SSP1-2.6 scenario.



Supplementary Fig. 18: Same as Supplementary Fig. 13, but for the SSP1-2.6 scenario.

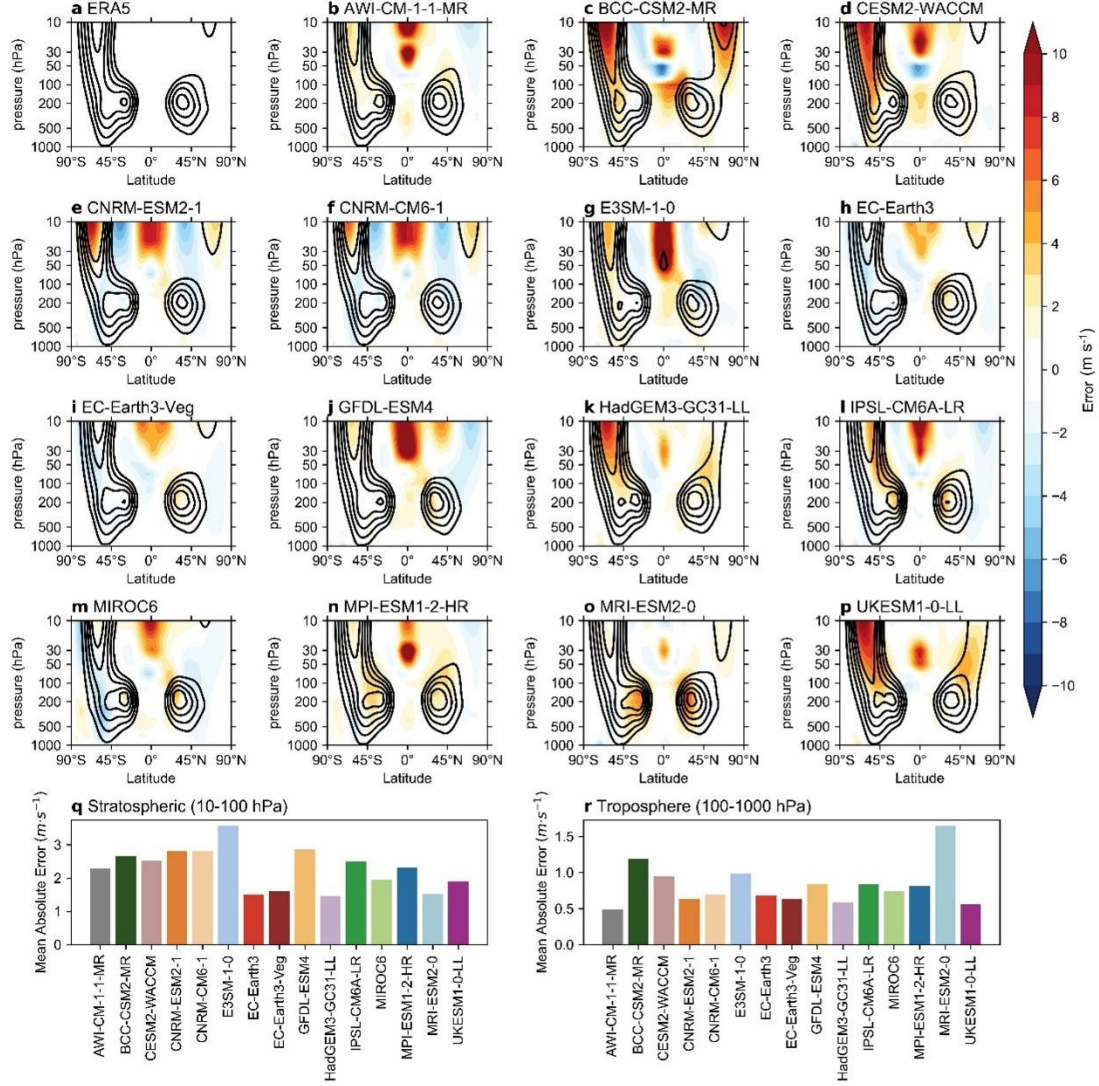
Performance of Tropospheric Key Variables in CMIP6 Models

We assess the ability of 15 CMIP6 models that are capable of simulating the quasi-biennial oscillation (QBO) to reproduce the key variables of interest in this study, including zonal wind, tropical convection, and sea surface temperature (SST). This additional evaluation is crucial for ensuring that the chosen models faithfully simulate these key variables and thus for underpinning the reliability of our conclusions.

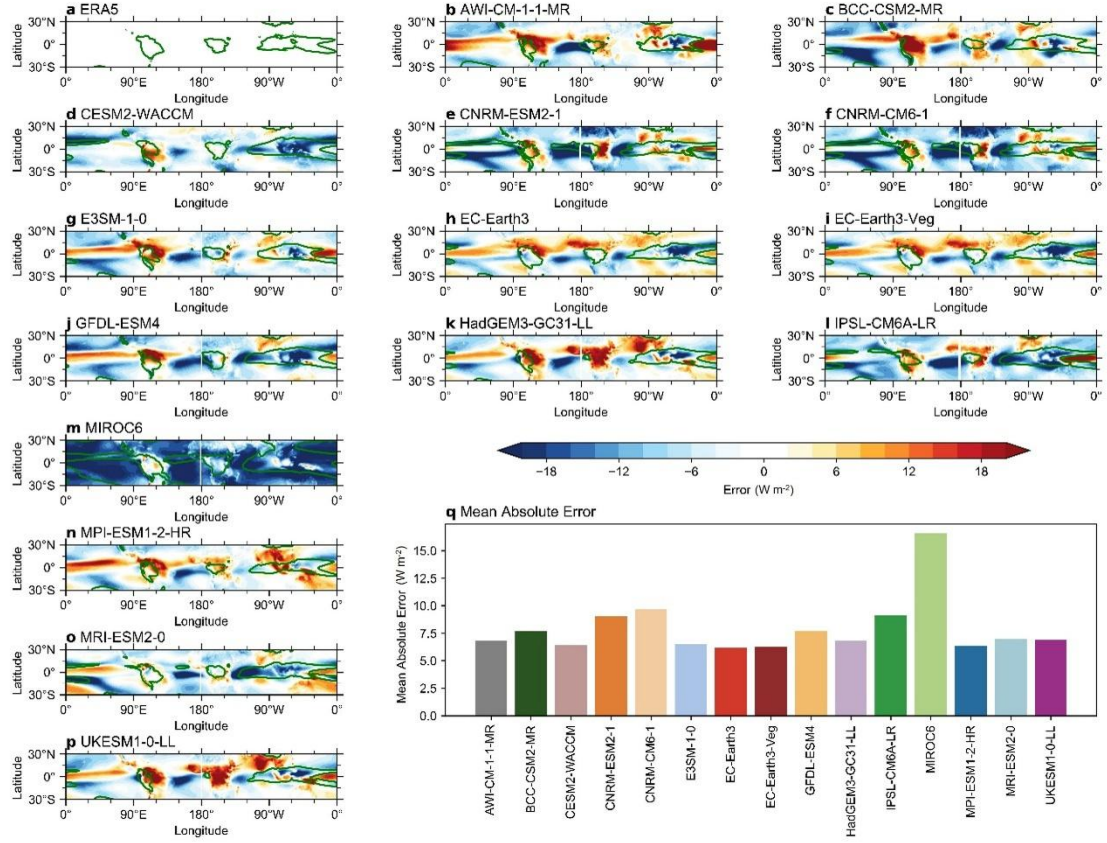
For zonal wind, tropical convection, and SST, we compared the climatological states simulated by the models with reanalysis data. As illustrated in Supplementary Fig. 19a–p, all models simulated the climatological modes of zonal wind nearly identically to ERA5 reanalysis data. We computed the mean absolute errors (MAE) for zonal-mean zonal wind in both the stratosphere (10–100 hPa) and troposphere (100–1000 hPa) (Supplementary Fig. 19q–r). Among the 15 models analyzed, the four selected models exhibited lesser deviations in simulating the stratospheric zonal wind relative to reanalysis data. However, MRI-ESM2-0 displayed the largest error in simulating tropospheric zonal wind. Given that our study focuses on the impact of QBO disappearance on the subtropical westerly jet, we excluded MRI-ESM2-0 from the analysis of tropospheric climate effects due to its significant bias in this region. Nevertheless, MRI-ESM2-0 remains suitable for analyzing the disappearance of the QBO itself and its associated mechanisms.

For tropical convection, most models accurately replicate the intense convection regions observed in the ERA5 data (Supplementary Fig. 20a–p). Based on mean absolute error (MAE) metrics, the four selected models performed well compared to the full ensemble (Supplementary Fig. 20q). Similarly, the climatological states of SST simulated by all models closely aligned with Hadley Centre data (Supplementary Fig. 21a–p), and the selected models showed strong performance in terms of MAE

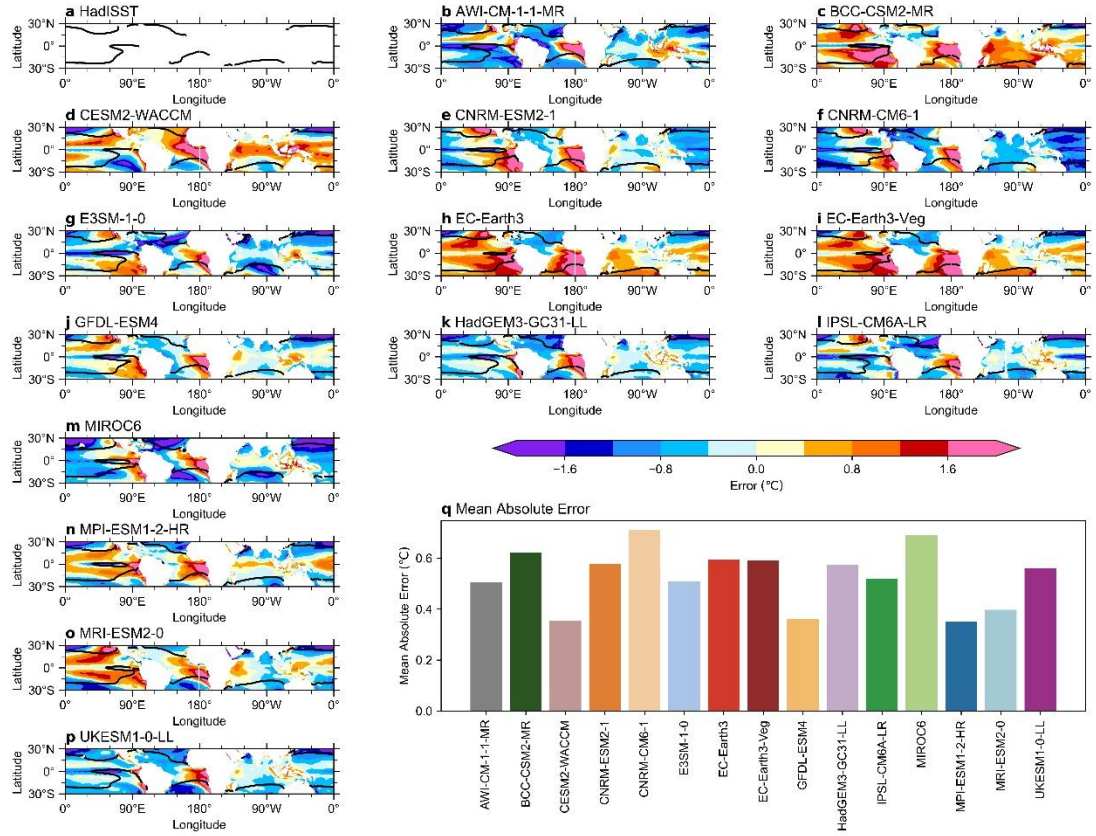
(Supplementary Fig. 21q). These findings suggest that, apart from the tropospheric zonal wind simulation in MRI-ESM2-0, the simulations of CESM2-WACCM, EC-Earth3-Veg, IPSL-CM6A-LR, and MRI-ESM2-0 are generally reliable for this study.



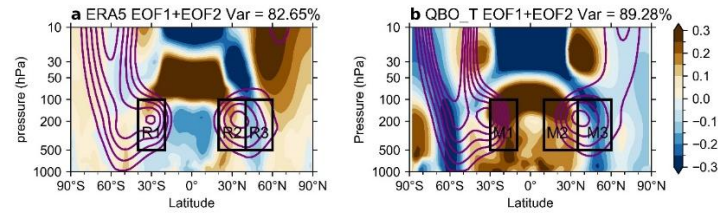
Supplementary Fig. 19: Zonal-mean zonal wind from ERA5 and model data for the period 1979–2014. **a** The climatological zonal-mean zonal wind from ERA5 data. **b–p** The differences between the model-simulated climatological zonal-mean zonal wind and ERA5 data, with shaded regions indicating these disparities. Contour lines represent the climatological zonal wind, with intervals of 5 m s^{-1} , the outermost contour corresponding to 10 m s^{-1} , and values increasing toward the center. **q–r** The mean absolute error in zonal-mean zonal wind between the model and ERA5 data in the stratosphere (10–100 hPa, 45°S – 45°N) and troposphere (100–1000 hPa, 45°S – 45°N), respectively.



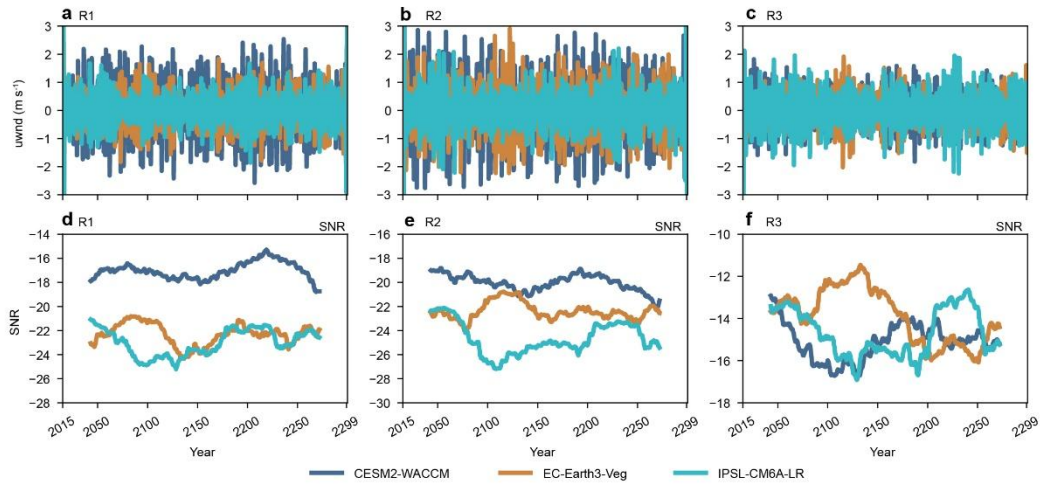
Supplementary Fig. 20: Outgoing longwave radiation from ERA5 and model data for the period 1979–2014. **a** The climatological outgoing longwave radiation from ERA5 data. **b–p** The differences between the model-simulated climatological outgoing longwave radiation and ERA5 data, with shaded regions indicating these discrepancies. Contour lines represent 240 W/m², with the enclosed areas highlighting regions of strong convection in the troposphere. **q** The mean absolute error (30°S–30°N, 0°–360°) of outgoing longwave radiation between the model and ERA5 data.



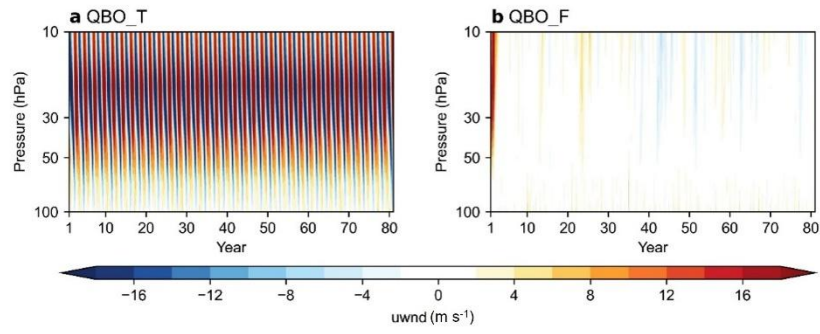
Supplementary Fig. 21: Sea surface temperature from Hadley Centre data and model data for the period 1979–2014. **a** The climatological sea surface temperature from Hadley Centre data. **b–p** The differences between the model-simulated climatological sea surface temperature and the Hadley Centre data, with shaded regions indicating these discrepancies. Contour lines represent 25°C. **q** The mean absolute error (30°S–30°N, 0°–360°) in sea surface temperature between the model and reanalysis data.



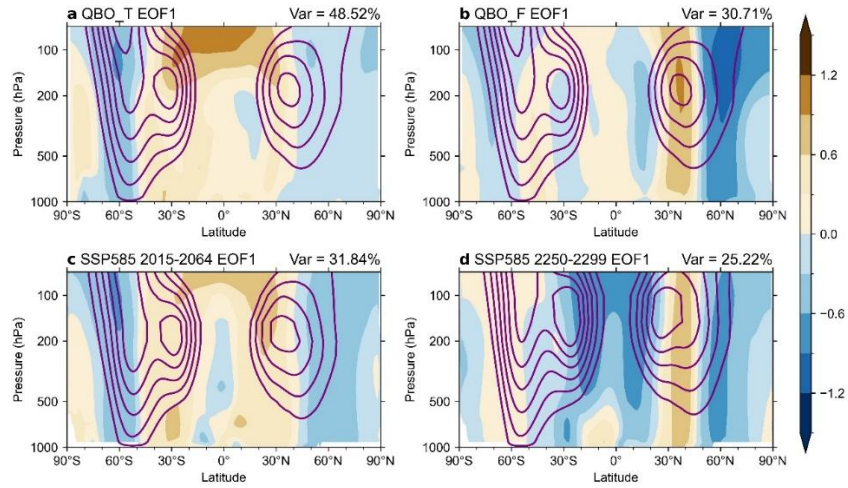
Supplementary Fig. 22: Tropospheric zonal wind anomaly mode associated with the quasi-biennial oscillation (QBO). Modes reconstructed from the first two EOFs of the 16–36 month zonal-mean zonal wind (see Methods). **a** ERA5 result. **b** QBO_T sensitivity experiment result. Purple contours indicate the climatological state of the zonal-mean zonal wind, with contour intervals of 5 m s^{-1} and the outermost contour at 10 m s^{-1} , increasing inward. Black boxes mark key regions where the QBO influences the tropospheric zonal wind.



Supplementary Fig. 23: Same as Fig. 3, but for the SSP1-2.6 scenario.



Supplementary Fig. 24: Time-height function of the tropical stratospheric zonal mean zonal wind (0° – 360° , 5° S– 5° N) from the sensitivity experiments. **a represents the experiment with QBO present (QBO_T), and **b** represents the experiment without QBO (QBO_F).**



Supplementary Fig. 25: EOF analysis of the 16 to 36 month band-pass filtered tropospheric zonal-mean zonal wind signal. The first EOF mode of the 16–36 month zonal wind from the sensitivity experiments with QBO forcing (**a**, QBO_T) and without QBO forcing (**b**, QBO_F) (see Methods). The first EOF mode of 16–36 month zonal wind from the SSP5-8.5 scenario during the first 50 years when the QBO is present (**c**) and the last 50 years after QBO disappearance(**d**). Purple contours indicate the climatological zonal-mean zonal wind for the corresponding periods, with contour intervals of 5 m s^{-1} . The outermost contour corresponds to 10 m s^{-1} , increasing inward.