Temperature trends in the northern winter middle atmosphere in relation to the QBO

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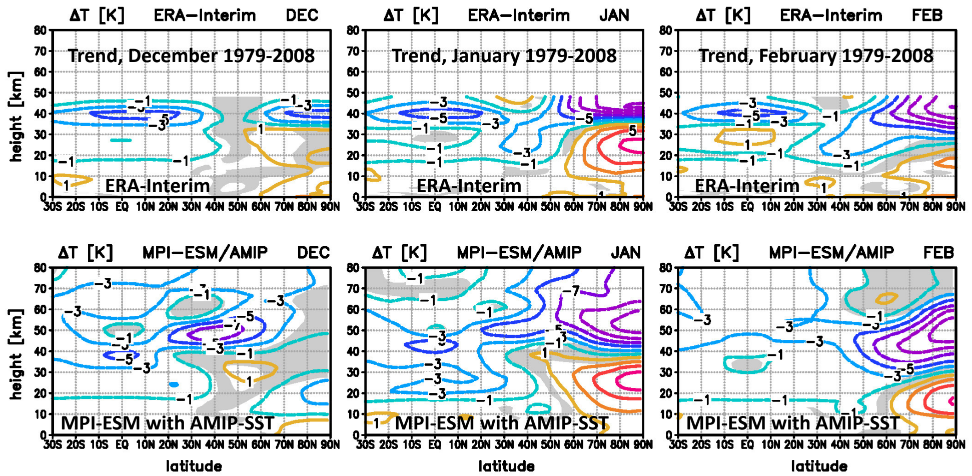
Summary

- Long-term trends due to anthropogenic greenhouse gas emissions are examined based on CMIP5-simulations with the MPI-ESM[1], which produces a realistic Quasibiennal Oscillation (QBO) in the tropical stratosphere (τ_{QBO}~28 months) (Scenarios **RCP4.5** and **RCP8.5**: increase of CO_2 up to ~650 ppm, ~1370 ppm).
- In the extra-tropics, the trends of mid-winter monthly means are much stronger during westerly (QBO-West) than easterly (QBO-East) phase of QBO.
- This trend behaviour is related to a CO_2-induced change in the sensitivity of the northern circulation to the QBO (a change in the extra-tropical stationary and local transient waves, where the QBO itself remains nearly unchanged).

[1] Earth-System-Model of the MPI-Met, Hamburg (Giorgetta et al., 2013; Schmidt et al., 2013)

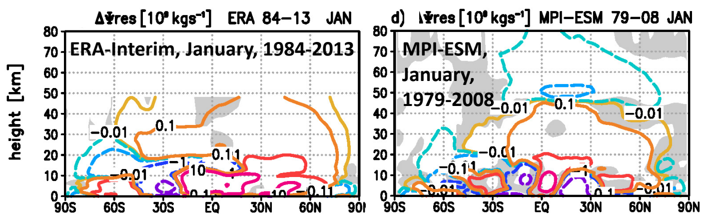
(1) Model Evaluation: MPI-ESM against ERA-Interim

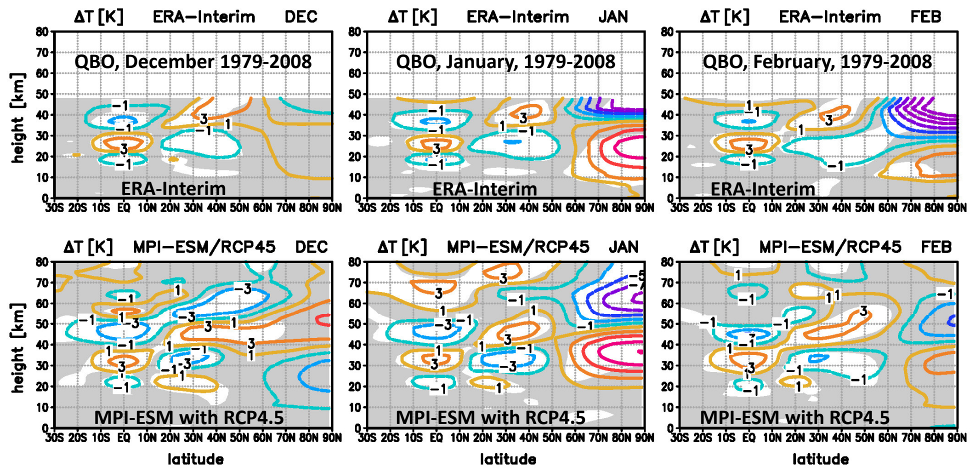
- Similar patterns of linear trend and QBO-signal in zonal mean temperature at high latitudes during mid-winter (warmer stratosphere, cooler mesosphere); the trends are forced by an increase (decrease) in meridional mass circulation.



Linear trend in monthly and zonal mean temperature (ERA-Interim 1979-2008 and MPI-ESM with AMIP-SST 1979-2008; grey-shaded areas: not significant)

Linear trend in residual stream function, January (ERA 1979-2008: stratospheric $\Delta\Psi_{res}$ negative over tropics)

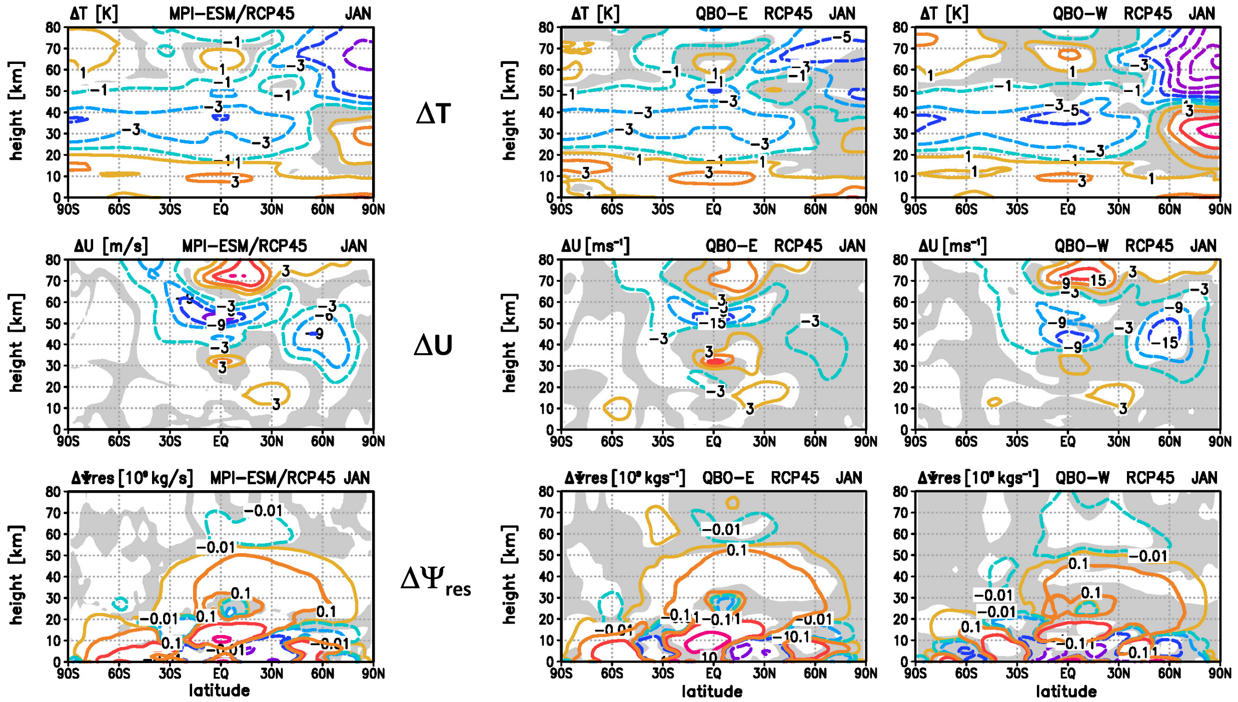




Differences QBO-East minus QBO-West mirror the "Holton-Tan effect" (*JAS*, 1980)

(2) Trend of zonal means in relation to QBO, RCP4.5, Jan 2006-2100

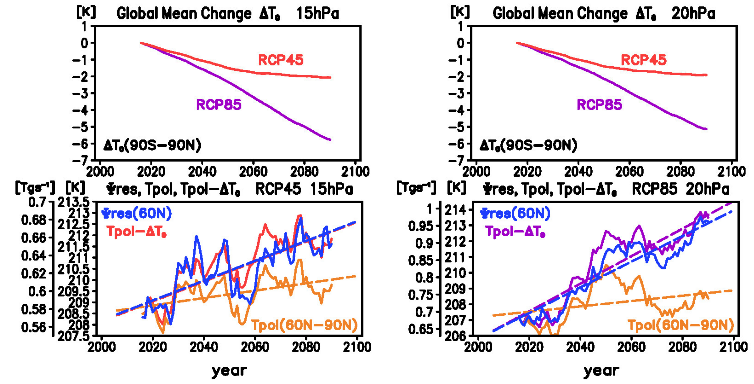
- Trends in temperature, zonal wind and residual circulation at high latitudes much larger for QBO-W than QBO-E; trend of QBO-W similar to difference QBO E–W (→ "Holton-Tan effect" disappears).



Linear trend (RCP4.5, 2006-2100) | Trend during QBO-East | Trend during QBO-West

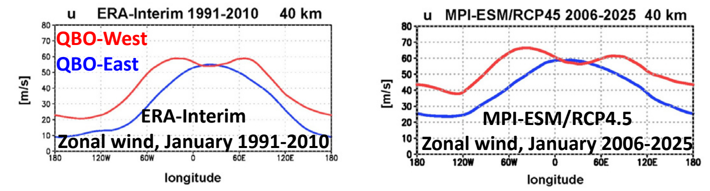
(3) Time series of the polar stratosphere

- Combination of radiation (→ global mean cooling ΔT_0,ΔT_0<0) and downwelling ($\Delta\Psi_{res}$ > 0 → dynamical heating of T_{pol})



Time series smoothed by a running mean over ±15 years.

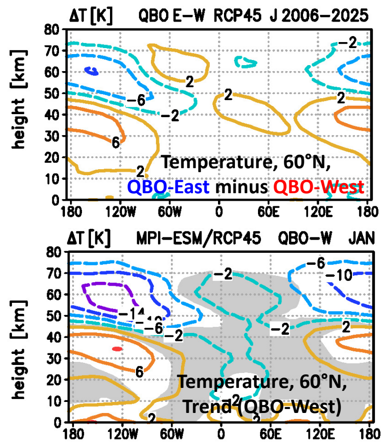
(4) Stationary waves at 60°N, 40km height



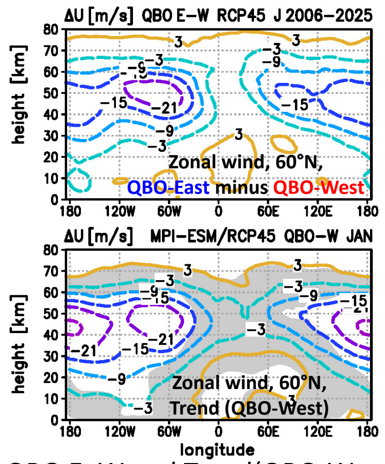
- Wave one (two) during QBO-E (QBO-W) (s. Holton&Tan,1980)

(5) Analysing the trend behaviour at 60°N and 10 hPa (~30 km), RCP4.5 – January 2006-2100

- Increase of wave-1 in QBO E–W and in the trend of QBO-West.

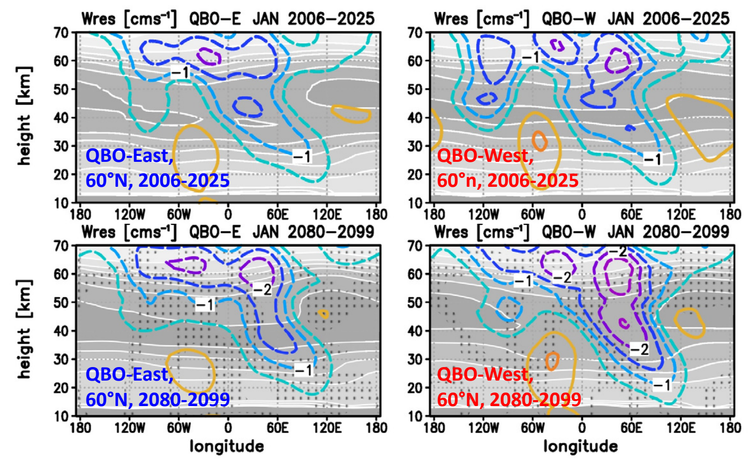


QBO E–W and Trend(QBO-West)

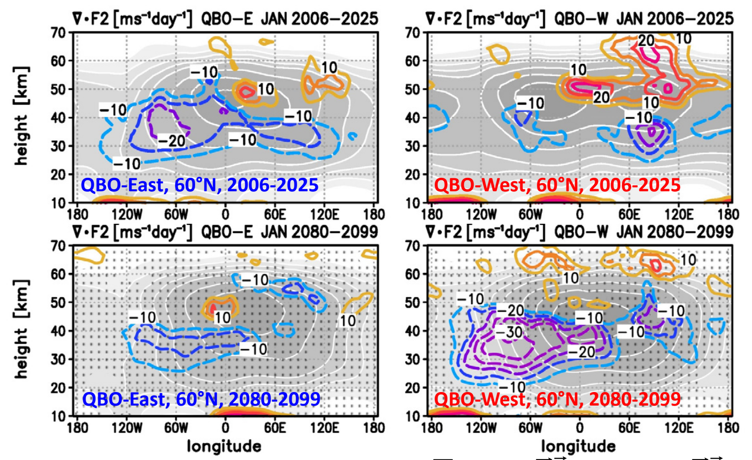


QBO E–W and Trend(QBO-West)

- Increase in downwelling (≈50%) over Northern Europe/West-Siberia and increase in local wave fluxes over North America ⇒ dissipation of the branch of the wave two excited by the Rocky Mountains (3D TEM diagnosis → Sato et al., *JAS*, 2013).



Time-mean vertical residual wind W_{res} (grey-shaded: H_2O, non-labelled isolines: 1 ppm; dots: trend not significant).



Time-mean wave flux divergence $f\,\overline{u}_{d_{res}} \approx \rho_0^{-1}\,\nabla\vec{F}_v - \beta f^{-1}\,\overline{S} \equiv \nabla\vec{F}2$ (grey-shaded: zonal wind u, non-labelled isolines: 10 ms^{-1}).

- Increase in wave-1 ⇒ eastward shift in phase via β-effect (shift where u<0) ⇒ planetary waves due to Rocky Mountains diminish

QG vorticity ($\zeta \approx \zeta_g$, $\beta = \partial f/\partial y$, $f = 2\Omega\sin\varphi$):

$d\zeta/dt \approx -\beta v + f_0 \partial\omega/\partial p \approx -(\zeta-\zeta_0)/\tau$

$(\zeta = \zeta(\theta) \approx \nabla^2\Psi \approx f_0\nabla^2\phi(\theta),\ v = \Psi_x,\ \phi = g\Phi)$

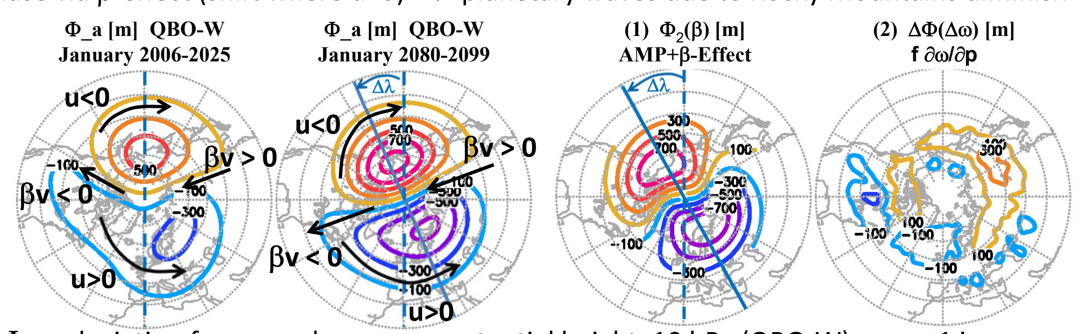
Stationary wave-1: $\Phi_{1,2} = A_{1,2}\cos(kx-\lambda_{1,2})$

(1) $\Delta\zeta(\beta) \approx \tau\,\beta\,\Delta v \;\Rightarrow\; \Phi_2(\beta)$

$A_2\cos(kx-\lambda_2) - A_1\cos(kx-\lambda_1) = \tau\beta k^{-1}\,(A_2\sin(kx-\lambda_2) - A_1\sin(kx-\lambda_1))$

$A_2/A_1 \approx 1.65 \;\Rightarrow\; \Delta\lambda \approx 30°$ (τ=7days)

(2) $\Delta\zeta(\Delta\omega) \approx \tau\, f\, \partial(\Delta\omega)/\partial p \;\Rightarrow\; \Delta\Phi(\Delta\omega)$



Φ_a: deviation from zonal mean geopotential height, 10 hPa (QBO-W): wave-1 increases ⇒ change in transport of planetary vorticity ⇒ planetary waves diminish where u<0; **$\Phi_2(\beta)$**: A_2=1.65·A_1 and Δλ via β-effect; **ΔΦ(Δω)**: increase in W_{res} ⇒ polar vortex weaker