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# The stratospheric wintertime response to applied extratropical torques and its relationship with the annular mode

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The response of the wintertime Northern Hemisphere (NH) stratosphere to applied extratropical zonally symmetric zonal torques, simulated by a primitive equation model of the middle atmosphere, is presented. This is relevant to understanding the effect of gravity wave drag (GWD) in models and the influence of natural forcings such as the quasi-biennial oscillation (QBO), El Ninõ-Southern Oscillation (ENSO), solar cycle and volcanic eruptions on the polar vortex. There is a strong feedback due to planetary waves, which approximately cancels the direct effect of the torque on the zonal acceleration in the steady state and leads to an EP flux convergence response above the torque's location. The residual circulation response is very different to that predicted assuming wave feedbacks are negligible. The results are consistent with the predictions of ray theory, with applied westerly torques increasing the meridional potential vorticity gradient, thus encouraging greater upward planetary wave propagation into the stratosphere.

The steady state circulation response to torques applied at high latitudes closely resembles the Northern annular mode (NAM) in perpetual January simulations. This behaviour is analogous to that shown by the Lorenz system and tropospheric models. Imposed *westerly* high-latitude torques lead counter-intuitively to an *easterly* zonal mean zonal wind ($\overline{u}$) response at high latitudes, due to the wave feedbacks. However, in simulations with a seasonal cycle, the feedbacks are qualitatively similar but weaker, and the long-term response is less NAM-like and no longer easterly at high latitudes. This is consistent with ray theory and differences in climatological $\overline{u}$ between the two types of simulations. The response to a a tropospheric wave forcing perturbation is also NAM-like. These results suggest that dynamical feedbacks tend to make the long-term NH extratropical stratospheric response to arbitrary external forcings NAM-like, but only if the feedbacks are sufficiently strong. This may explain why the observed polar vortex responses to natural forcings such as the QBO and ENSO are NAM-like. The results imply that wave feedbacks must be understood and accurately modelled in order to understand and predict the influence of GWD and other external forcings on the polar vortex, and that biases in a model's climatology will cause biases in these feedbacks.